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WATER RESOURCES ACTIVITIES IN THE UNITED STATES. EVAPO-TRANSPIRATION REDUCTION. PART I. PHREATOPHYTIC AND HYDROPHYTIC PLANTS ALONG WESTERN STREAMS. PART II. VEGETATION MANAGEMENT AND WATER YIELDS IN THE 17 WESTERN STATES

Select Committee on National Water Resources, U. S. Senate

February 1960

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86th Congress
2d Session

COMMITTEE PRINT NO. 21

WATER RESOURCES ACTIVITIES IN THE UNITED STATES

EVAPO-TRANSPIRATION REDUCTION

SELECT COMMITTEE ON NATIONAL WATER RESOURCES
UNITED STATES SENATE

PURSUANT TO

S. Res. 48

EIGHTY-SIXTH CONGRESS

FEBRUARY 1960

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STATEMENT BY THE CHAIRMAN

FEBRUARY 2, 1960.

To the Members of the Senate Select Committee on National Water Resources:

Under the provisions of Senate Resolution 48, our committee is directed to consider new technical methods and processes for increasing the usefulness of water resources, including among others, the reduction of evapo-transpiration. Evapo-transpiration is the transfer of water to the atmosphere from the leaves of plants and other surfaces by two methods. First, through the evaporation of recently fallen precipitation which is intercepted before it reaches the ground, and second, through transpiration, which is the release of water vapor created in the process of photosynthesis, an essential process in plant growth.

Results of recent resear.h indicate that vegetal cover in water-short areas could be managed in such manner as to reduce evapo-transpiration losses from watershed areas and thereby increase the amount of water available for ground water recharge and runoff.

In order to secure for the committee the best available information on this subject, I asked the Department of Agriculture to prepare a report on vegetation management as a means of increasing water yield so as to give us background for use in considering steps that might be taken to encourage research and developments in this field. I asked that attention be given to programs carried out by other agencies and also other non-Federal interests, and invited the Department to make recommendations as to future research and developmental work in this field.

The Department's report indicates that opportunities for improved water yields through management of vegetation appear favorable on about 15 percent of the area of the 17 Western States with a possibility for increasing water yields in amounts ranging from about 1 to 6 inches in certain forest areas of heavy winter precipitation to as low as one-fourth inch in the piñon-juniper areas of very low precipitation. No increase at all is possible on semiarid lands covered with grass and shrub which make up the great bulk of the area of the West. Possibilities of reduction of losses from phreatophytes, water-loving plants which cause a major loss of water along rivers in the Western States, are also discussed, with an indication that a saving of up to 25 percent of water now lost through these plants appears possible. This saving would amount to about 6 million acre-feet per year. The report is qualified by the statement that there are insufficient economic data and analysis techniques available at this time upon which to base decisions to use lands for water yield alone as against other uses. The report concludes with suggestions as to research in the field of vegetal management which might furnish information which would increase our knowledge in this field.

The area in the field of evapo-transpiration reduction which shows promise of yielding the most immediate water savings is the reduction of losses from phreatophytic and hydrophytic plants along western streams. These are plants which have their roots in the groundwater or which grow in water and which result in the transpiration of large amounts of water into the atmosphere. Because of the experience of agencies in the Department of the Interior in this field, I asked that Department to prepare a report giving us background and suggestions as to future action which might be taken to encourage action in this area.

The report of the Department of the Interior on phreatophytic and hydrophytic plants along western streams indicates that nonbeneficial phreatophytes in the 17 Western States cover nearly 16 million acres and that they may discharge from 20 million to 25 million acre-feet of water into the atmosphere annually. The report discusses methods which are being used to control phreatophytes and the need for future research in the field of water use by phreatophytes, and the hope is expressed that as much as one-quarter of the total estimated savings can be accomplished by 1980 and one-half by the year 2000.

Both reports will be of interest to you, to other members of the Senate, and to others interested in the conservation of water in the West, and therefore I am having them printed as one of our committee prints covering all aspects of water resources activities in the United States.

ROB'T S. KERR,
Chairman, Select Committee on
National Water Resources.

COMMUNICATIONS

AUGUST 26, 1959.

Hon. FRED A. SEATON,
The Secretary of the Interior,
Department of the Interior,
Washington, D.C.

MY DEAR MR. SECRETARY: Reference is again made to my letter of June 15, 1959, relative to the work of the Select Committee on National Water Resources.

One of the means of increasing the usefulness of our available water resources to which the committee will need to give attention is the reduction of losses from phreatophytic and hydrophytic plants along western streams. Losses from these plants appear to be of such magnitude as to justify the preparation of a separate report for the committee on this subject. In view of the long experience of agencies of the Department of the Interior in obtaining information with respect to water losses from this source, it is requested that the Department prepare a report for the committee on measures for reducing water losses caused by unwanted vegetation along natural water courses in the United States.

It is understood that there is an interdepartmental committee dealing with this subject and we would expect the Department's report to cover all the work being done by the other Federal agencies represented on that committee as well as, to the extent available, work being done by State and local agencies.

Principal objective of the report should be to furnish background for the committee's use in considering steps that might be taken to encourage reduction of losses from phreatophytic and hydrophytic growths. The report should contain a brief description of areas and streams in the various water resource regions in which these losses occur, giving nature of the plants and amount of water consumed in relation to streamflow. Possible reduction of losses should be discussed together with measures that have been taken or are under consideration for avoidance or reduction of losses. Benefit-cost relationships should be given for such measures to the maximum extent practicable, together with estimates of amounts of water conservation possible of achievement by 1980 and 2000.

The report should conclude with the Department's suggestions as to future action which should be taken in this field, with comments as to the role which the Federal Government might take.

We would like the subject to be covered in a summary report of not more than 10,000 words with whatever tables, charts, appendixes, and graphic illustrations as may be considered necessary. It would be most helpful if this report could be furnished the committee by November 15, 1959.

The committee staff will be glad to discuss any problems which may arise in the preparation of the report with representatives of the Department.

Sincerely yours,

ROB'T S. KERR, *Chairman.*

U.S. DEPARTMENT OF THE INTERIOR,
OFFICE OF THE SECRETARY,
Washington, D.C., December 16, 1959.

Hon. ROBERT S. KERR,
Chairman, Select Committee on National Water Resources,
U.S. Senate, Washington, D.C.

DEAR SENATOR KERR: There is enclosed in accordance with your request of August 26 a report on "Phreatophytic and Hydrophytic Plants Along Western Streams." The report deals primarily with saltcedar, (Tamarix gallica L.), the No. 1 problem plant among the phreatophytes. This approach was taken due to the magnitude of the saltcedar problem and the fact that the predominance of accomplishments to date and information available on the subject deals with it. Several of the publications listed in the report are currently out of print and not available at this time. The supply of others is very limited. We have been able, however, to furnish one copy of each for general use of the committee.

To date, very little has been accomplished in this field with respect to detailed benefit-cost analysis. We have attempted to present such actual cost data as are available. In addition, the report sets forth in a general way an estimate of the water salvage which might be expected in the 17 Western States as well as some of the major river basins within the area.

No projections have been made relative to the water conservation possible of achievement in this manner during any given period. It is hoped that at least one-fourth of the total estimated savings can be accomplished by 1980 and one-half by the year 2000.

Sincerely yours,

ELMER F. BENNETT,
Acting Secretary of the Interior.

CONTENTS

PART I

PHREATOPHYTIC AND HYDROPHYTIC PLANTS ALONG WESTERN STREAMS

	Page
Statement by the chairman	III
Communications	V
Introduction	1
Definition	1
Problem	1
Plant species	1
No. 1 problem plant	1
General infestation	1
Consumptive use	2
Distribution and extent of infestation	2
Location of major infestations	3
Rate of spread	3
Density	3
Area of infestation by drainage basins	3
Estimated annual water use by drainage basins	3
Problem areas	3
Gila River	5
Pecos River	6
Rio Grande	6
Colorado River	6
Status of knowledge and need for further research in the field of water use by species of phreatophytes	6
Advance in plant identification	6
Plant distribution and areal density	6
Water use	6
Effect on water quality	7
Beneficial uses	7
Ecological factors	7
Methods of eradication	7
Effectiveness of salvage methods	7
Accomplishments in the field of phreatophyte control	8
Cost of eradication	10
General statement	10
Proposed project estimates for Safford Valley	10
Costs by various methods of treatment	10
References	11
List of publications and documents related to phreatophytes	11

ILLUSTRATIONS

Figure 1. Preliminary map of saltcedar distribution in Western United States ..... faces p. 3
Figure 2. Spread of phreatophytes along Pecos River Channel from Alamogordo Dam to the State line ..... faces p. 4
Figure 3. Increase of saltcedar area, Rio Grande Valley, Bernardo to San Marcial, N. Mex 4

PART II

Vegetation Management and Water Yields in the 17 Western States

	Page
Communications	15
Highlights	17
Introduction	18
The role of vegetation in improving water yields	19
Interception	19
Infiltration and percolation	19
Transpiration	19
Evaporation	20
Other factors related to water yields	20
Relation of water to other land uses	20
Status of knowledge	21
Forest lands (general)	21
Forests in the snowpack zone	21
Normal water yield	23
Possibilities for improving water yield	23
Impacts of a program to improve water yield	25
Summary	25
Douglas-fir-hemlock-redwood forests	25
Interior ponderosa pine and Douglas-fir	25
Normal water yield	26
Possibilities for improving water yield	27
Thinning of sapling and pole-size stands	28
Timber harvest in sawtimber stands	28
Converting ponderosa pine to grass	28
Summary	29
Chaparral and woodland of California and Arizona	29
Normal water yield	29
Possibilities for improving water yield	29
Conversion to grass	30
Summary	31
Piñon-juniper	31
Normal water yield	32
Possibilities for improving water yield	32
Summary	32
Semiarid grass and shrub	32
Normal water yield	33
Possibilities for improving water yield	34
Other possibilities of vegetation management	34
Summary	34
Phreatophytes and riparian vegetation	34
Possibilities for improving water yield	35
Summary	36
Alpine zone	36
Possibilities for improving water yield	36
Application requirements and limitations	36
Research	39
Recommendations for further research	39
Interception	39
Infiltration and percolation	39
Evaporation	39
Transpiration	40
Management of brush and rangelands	40
Management of forests trees and stands	40
Management using fertilizers	40
Management of phreatophytes and riparian vegetation	41
Management for erosion control	41
Water yields from small and large watersheds	41
Economic research	41
References	42

ILLUSTRATIONS

	Page
Figure 1. Areas of lodgepole pine and Engelmann spruce-fir	22
Figure 2. Areas of mixed conifer and true fir	23
Figure 3. Areas of Douglas-fir (Pacific), hemlock, and redwood forests	26
Figure 4. Areas of ponderosa pine and Douglas-fir (Interior)	27
Figure 5. Areas of chaparral, etc., and pifion-juniper	30
Figure 6. Areas of semiarid grass and shrub	33

50981—60——2

EVAPO-TRANSPIRATION REDUCTION

PART I

PHREATOPHYTIC AND HYDROPHYTIC PLANTS ALONG WESTERN STREAMS

INTRODUCTION

Phreatophyte is the name given to a group of plants that tap ground water and habitually depend on it for their water supply. The name, derived from the Greek, means "well plant" and is a very apt description for each plant is actually a small pump that supplies its daily needs by drawing from the ground-water reservoir. Phreatophytes are commonly found lining the banks of streams, on flood plains, on valley bottoms, and on lowlands—places where the water table lies at shallow depth.

The phreatophyte problem is one that is peculiar to the arid and semiarid regions of Western United States. Although phreatophytes occur in both humid and arid regions their impact is greatest in the regions of short water supply. Here there is keen competition between the plants and man for the use of the available water. The plants having an established connection with the ground-water reservoir have first call on the water, leaving for man that which they do not use. The use of water by the plants is great, for the climate of desert regions is favorable for a high rate of transpiration.

The water consumed by most phreatophytes is largely wasted, for most of the plants have a low or negligible economic value. This water is often referred to as consumptive waste to distinguish it from the water used in the growing of cultivated crops and other vegetation of high economic value, commonly referred to as beneficial consumptive use. A reduction in the amount of water consumptively wasted conserves and makes available for salvage an amount equal to the reduction. The amount that will actually be salvaged depends upon the efficiency of the salvage operations. In the arid regions of Western United States, where the phreatophyte problem is most acute, consumptive waste is one source of reclaimable water.

There are over 70 plants that have been classified as phreatophytes in Western United States. This group does not belong to any one genus or family but includes many genera and many species. Not all are problem plants for some, such as alfalfa (*medicago* spp.), are valuable as forage plants.

The No. 1 problem plant is saltcedar (*Tamarix gallica* L.). In the Southwest virtually every stream of consequence supports a dense growth of this vigorous, aggressive, and rapidly spreading plant. Its annual rate of water consumption is greater than that of any other phreatophyte. Five acre-feet per acre is not uncommon and under ideal conditions of growth and density it may exceed 9 acre-feet per acre. Other important problem plants that use a substantial amount of water are willow (*Salix* spp.), cottonwood (*Populus* spp.), mesquite (*Prosopis* spp.), and greasewood (*Sarcobatus vermiculatus* T.). Of lesser importance, but still a problem in many States, are seepwillow (*Baccharis glutinoso* P.), alder (*Alnus* spp.), arrowweed (*Pluchea servica* C.), giant reedgrass (*Phragmites communis* T.), and camelthorn (*Alhagi camelorum* F.).

Climate, particularly temperature, controls the occurrence of some phreatophytes while others are relatively unaffected. Saltcedar, mesquite, seepwillow, and arrowweed thrive best in the warm climate of the Southwest. Some, such as greasewood, prefer the cold desert areas of the Great Basin, while others like willows, cottonwood, and saltgrass, have a wide range of climatic tolerance and grow from Canada to Mexico at altitudes ranging from sea level to 8,000 feet.

Estimates based on incomplete data indicate that the area occupied by phreatophytes in the

17 Western States is nearly 16 million acres. Phreatophytes in these States may discharge between 20 and 25 million acre-feet into the atmosphere annually (Robinson, 1952). The estimate includes only those plants considered nonbeneficial to the area from a water-use standpoint. Such beneficial plants as alfalfa were not included. It takes into consideration the fact that plants in a warm climate use more water than those in cooler climates. The area of phreatophytes in the States of California, Arizona, New Mexico, Nevada, Utah, and Colorado in Southwestern United States, based on the most recent data, is estimated as 7 million acres, and the water consumed by the plants as from 10 to 12 million acre-feet per year. For the States of Arizona and New Mexico, the estimated area is a little less than 1 million acres and the estimated annual water use is between 2½ and 3 million acre-feet.

The annual rate of water consumption by phreatophytes ranges widely according to the plant species and to local conditions. Under the same conditions some species consume large quantities of water, others much less. The rate of consumption will also vary from one locality to another. The variation in the rates of use is largely dependent upon three principal factors—depth to the water table, climatic conditions, and amount of foliage. The rate is highest when the water table is shallow, the climate hot and dry, and the growth dense.

The amount of foliage is affected by two variables, areal density and vertical density. A uniformly accepted formula for the determination of these variables has, as yet, not been developed. Their product is called volume density. Areal density relates to the numerical density of the plants in a unit area with respect to the maximum possible, and vertical density relates to the vertical depth of fronds with respect to the maximum possible. The maximum possible growth would be one of 100 percent volume density. The use of water varies almost in direct proportion to the volume density of the growth.

Determinations of the use of water by some of the more common species of phreatophytes have been made from time to time at different localities in the West. With the exception of alder and mesquite all of these determinations have been made for plants grown in tanks. The phreatophytes and localities where the determinations were made are listed in the following table. Information is included on the volume density and depth to the water table, when known.

TABLE 1.—*Annual rate of water use by some common phreatophytes in Western United States*

Plant	Annual rate including precipitation	Volume density	Depth to water	Locality
	Acre-feet per acre	*Percent*	*Feet*	
Alder	5.3	.....	.....	Santa Ana River, Calif.
Batamote or seepwillow	4.7	100	6	Safford Valley, Ariz.
Cottonwood	7.6–5.2	100	3–4	San Luis Rey River, Calif.
Do.	6.0	100	6	Safford Valley, Ariz.
Greasewood	2.5–.08	.....	.....	Escalante Valley, Utah.
Mesquite	3.3	100	10	Safford Valley, Ariz.
Saccaton	4.0–3.5	.....	.....	Pecos River Valley, N. Mex.
Saltcedar	5.5–4.7	.....	.....	Do.
Do.	9.2–7.3	100	4–7	Safford Valley, Ariz.
Saltgrass	4.1–1.1	.....	1.5–5	Owens Valley, Calif.
Do.	2.9–1.1	.....	2–4	Santa Ana, Calif.
Do.	2.3–1.1	.....	.3–2.1	San Luis Valley, Colo.
Do.	4.5	.....	2.0	Carlsbad, N. Mex.
Do.	2.6	.....	.65	Isleta, N. Mex.
Do.	4.0–.8	.....	.4–3.1	Los Griegos, N. Mex.
Do.	1.9	.....	2.2	Mesilla Dam, N. Mex.
Do.	2.3–1.6	.....	1.9–2.6	Escalante Valley, Utah.
Do.	2.9	.....	2.0	Vernal, Utah.
Willow	4.4	.....	2.0	Santa Ana, Calif.
Do.	2.5	.....	1.1	Isleta, N. Mex.

DISTRIBUTION AND EXTENT OF INFESTATION

While the problem of phreatophytes and consumptive waste of water by them is present in all western river basins, it is more acute in some than in others. The magnitude of the problem depends upon several factors such as the characteristics of stream channels, the climate, the depth to ground water, and the species and density of phreatophytes. It is greatest for streams with wide flood plains that support dense growths of vegetation having large water demands.

Specific data on the distribution and extent of infestation of phreatophytes is available in only a few river basins. For some streams the information is general—as, for example, the Humboldt River in Nevada, which is known to be heavily infested with willow and to support a generous growth of greasewood. The Green River in its 437-mile course through Colorado and Utah passes through several valleys where the stream is bordered by a total of 40,000 acres of flood plains much of which is covered with phreatophytes. The average daily depletion in flow for a 21-day period in September 1948, resulting from evapotranspiration in the flood plain, was, according to Thomas (1952), 552.4 acre-feet, equivalent to a continuous flow of 278 cubic feet a second.

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

B

115°
113°
111°
109°
107°
105°
103°
101°
99°
97°
95°
BRITISH POSSESSIONS
CANADA
MONTANA
NORTH DAKOTA
SOUTH DAKOTA
WYOMING
NEBRASKA
COLORADO
KANSAS
Havre
Fort Benton
Great Falls
MISSOURI RIVER
Glasgow
Williston
Minot
Bottineau
Devils Lake
Grand Forks
Helena
Bozeman
Livingston
Billings
Miles City
Dickinson
Bismarck
Jamestown
Fargo
Valley City
Wahpeton
Fergus Falls
Aberdeen
Sheridan
Buffalo
Deadwood
Lead
Pierre
Chevenne River
Grand River
Watertown
Huron
Mitchell
Sioux Falls
Sioux City
Yankton
Spencer
Idaho Falls
Pocatello
Lander
Hot Springs
White River
Douglas
Chadron
Niobrara River
Alliance
North Platte River
Rawlins
Laramie
Cheyenne
Sidney
Ogden
Salt Lake City
Provo
Evanston
Green River
Rock Springs
Fort Collins
Greeley
Boulder
Denver
South Platte River
North Platte
Grand Island
Kearney
Platte River
York
Lincoln
Hastings
Holdrege
McCook
Republican River
Fairbury
Beatrice
Falls City
Omaha
Council Bluffs
Nebraska City
Norton
Colby
Concordia
Atchison
Leavenworth
Topeka
Lawrence
Junction City
Salina
Ellsworth
Smoky Hill River
Colorado Springs
Pueblo
Canon City
Leadville
Aspen
Grand Junction
Gunnison
Ouray
Arkansas River
La Junta
Lamar
Garden
Hutchinson
Wichita
Emporia
Iola
Fort Scott
Winfield
Arkansas City
Anthony
Enid
Woodward
Cimarron River
Raton
Trinidad
Durango
Mancos
Animas
Gila
Little Colorado
Utah L.
Eureka
Nephi
Spring
Mt. Pleasant
Ephraim
Manti
Provo River
Weber River
Bear River
Malad
Montpelier
Logan
Brigham
Strongs
Bear L.

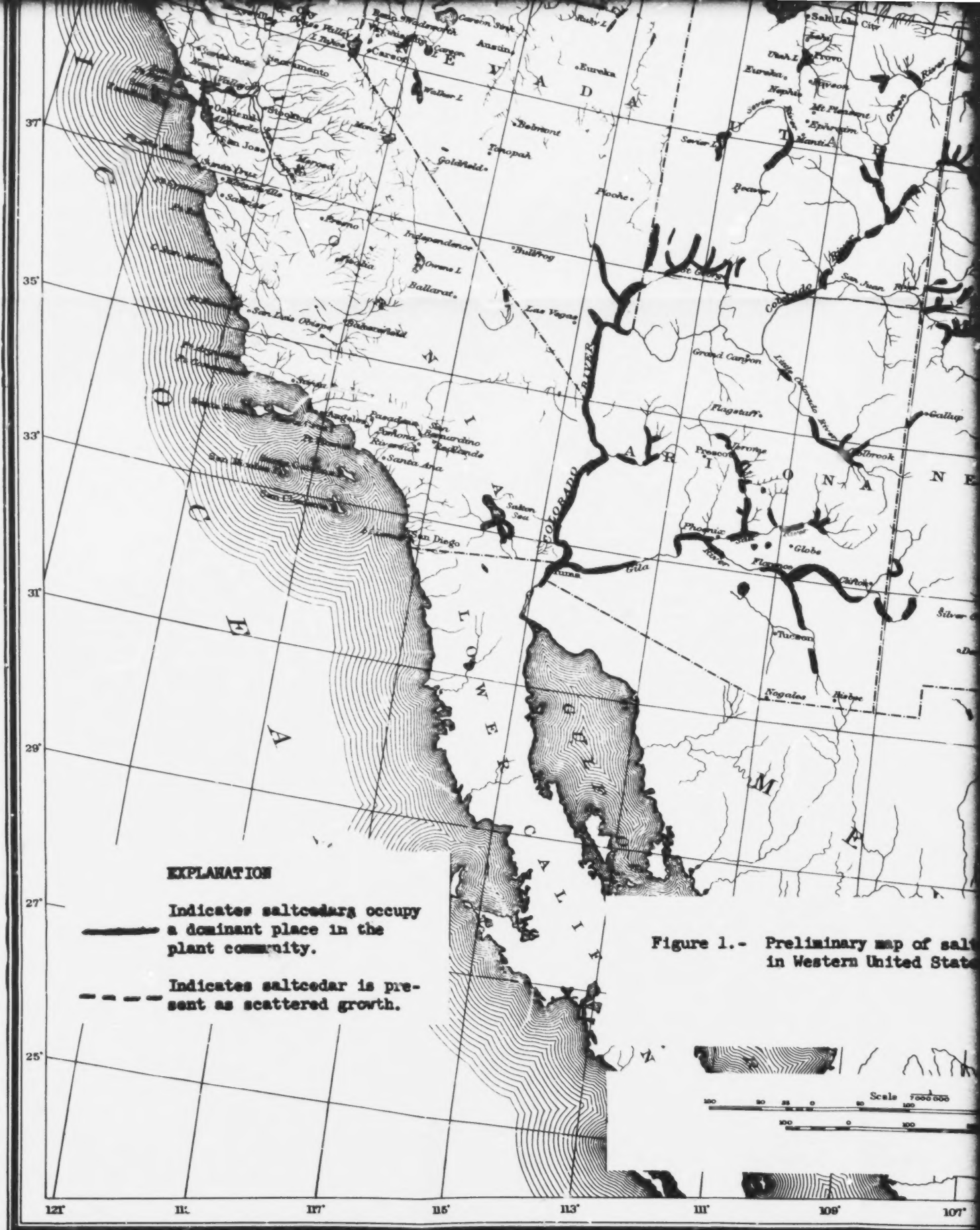

Figure 1.- Preliminary map of salt
in Western United State

ry map of saltcedar distribution
n United States.

50981 O - 60 (Face p. 3)

More data are available on the distribution and extent and rate of infestation of saltcedar than for any other species. This plant, which is native to the Mediterranean region, was introduced into Southwestern United States before the turn of the century. Since then it has thrived and spread rapidly throughout the Southwest and in recent years into and beyond the Great Basin to northern Wyoming and eastern Oregon, as shown in figure 1. The distribution of saltcedar as shown on the map of Western United States was compiled from information supplied by Federal and State agencies and interested individuals in an attempt to show the extent to which this plant has invaded the West. Data on the distribution of the plant in Texas are especially scanty. Even though incomplete, the map is believed to indicate with a fair degree of accuracy the present extent and distribution of saltcedar in the 17 Western States.

Data on the rate of spread of saltcedar are available for two streams in New Mexico—the Pecos River and the Rio Grande. Records indicate that before 1912 there was no saltcedar in the Pecos Basin. The first report of a few seedlings was in 1912, and by 1915 these had spread to cover about 600 acres. By 1925 they were estimated to cover 12,300 acres, and in 1939, 15,200 acres. The phenomenal spread from 1937 to 1953 between Alamogordo Dam and the Texas State line is illustrated in figure 2. In 1956 there was a rapidly expanding growth of approximately 5,000 acres in the delta above Alamogordo Reservoir. By 1956 the total area of saltcedar in the Pecos River Basin of New Mexico, including the delta above Alamogordo Dam, had reached 42,500 acres (Thompson, 1957) and now (1959) it is believed to be between 45,000 and 50,000 acres.

In the Rio Grande Basin saltcedar was first reported in the area south of Mesilla Park about 1910. The Rio Grande joint investigation surveyed the area and mapped 3,510 acres in 1936. Since that time it has increased rapidly. Figure 3 (Thompson, 1957a) is a portrayal of the increase of the area infested and of the density of growth, for a 60-mile reach of the Middle Rio Grande Valley from Bernardo to San Marcial from 1914 to 1955. Based on the rate of increase from 42,000 acres in 1950 to 52,000 acres in 1955, the area of saltcedar in this reach is estimated as 60,000 acres in 1959. For the Rio Grande Basin in New Mexico the present area of saltcedar growth may well be in excess of 100,000 acres.

Figures 2 and 3 show that not only is the area of infestation of saltcedar increasing rapidly but also that there is a rapid increase in density of growth. According to figure 2 the area of dense growth in the Pecos River Basin in 1939 was only 490 acres. Seven years later, in 1946, this had increased to 5,895 acres, or 12 times the 1939 area. In 1950 it was 7,715 or 16 times the 1939 figure. The same trend is apparent for the Rio Grande Basin in figure 3. The area of 100-percent density increased from 610 acres in 1935 to 13,420 acres in 1955, or 22 times the 1935 area.

Eventually, when the area becomes fully covered, the spread of saltcedar in an area must cease, but the increase in density will continue until the entire area of growth has reached its maximum density. As the density increases, the draft of ground water increases in about the same proportion. A growth of 100-percent density uses about twice as much water as a growth of 50-percent density.

During the past two decades, as the phreatophyte problem has aroused more and more awareness of consumptive waste, studies and surveys have been made of infested basins, subbasins, and local areas to determine the extent of phreatophyte growth and amount of water consumed. The results of these studies and surveys and the year in which they were made is compiled in table 2.

PROBLEM AREAS

In all of the river basins and valleys listed in the foregoing table, the use of water by phreatophytes presents a water-waste problem. In some of the basins the waste is greater than in others. The available data indicate that the amount of waste is greatest for those streams in Arizona and New Mexico and for the Lower Colorado River.

In addition to the extreme high consumption of water, phreatophytes in many instances present other problems. Some, particularly saltcedar, invade and choke normal overflow channels of streams, greatly reducing their water-carrying capacity. As a result, in times of flood the water spreads over large areas that normally would not be flooded, endangering lives and damaging property. Dense growth reduces the velocity of overbank flows. As

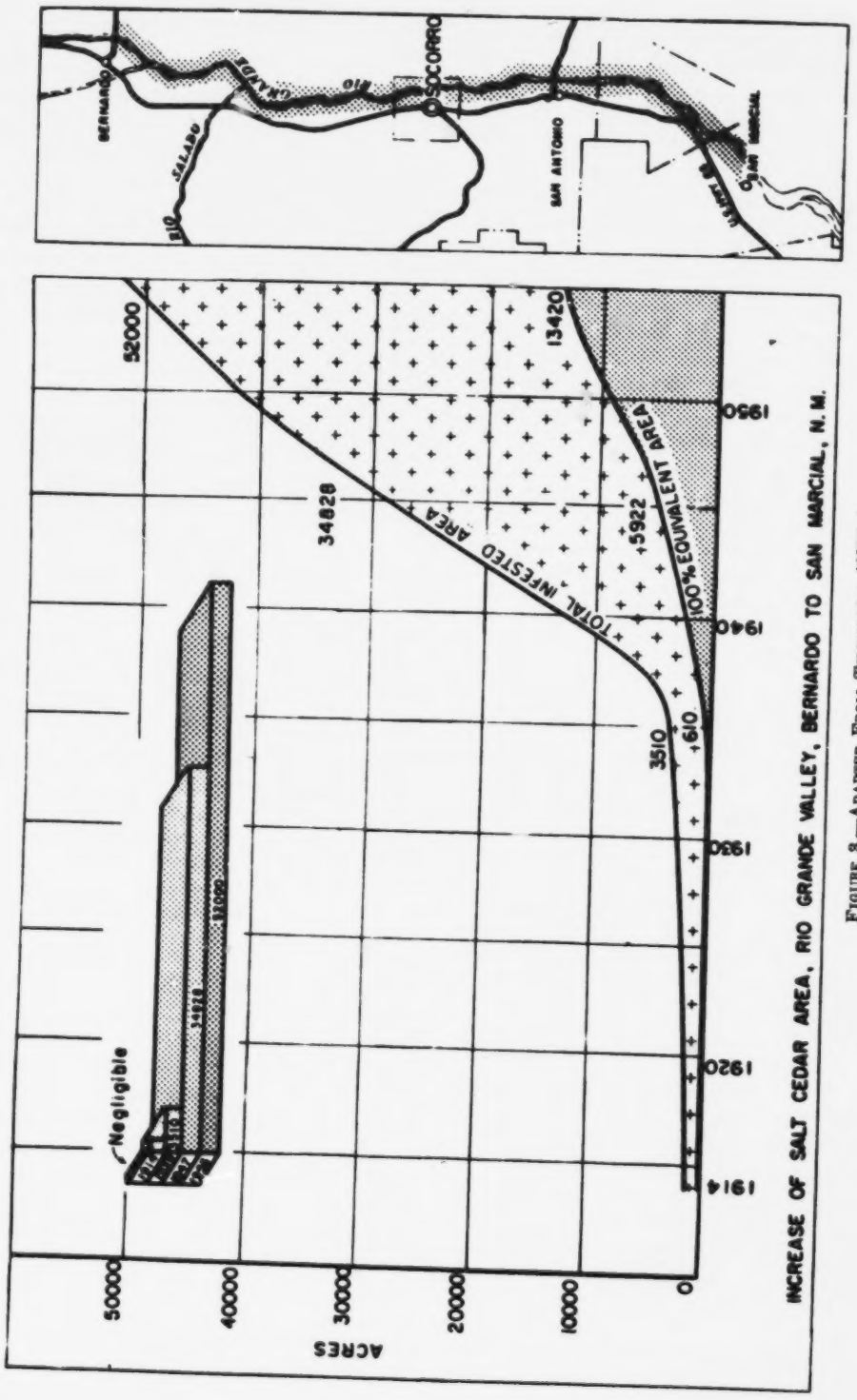

FIGURE 3.—ADAPTED FROM THOMPSON (1957a).

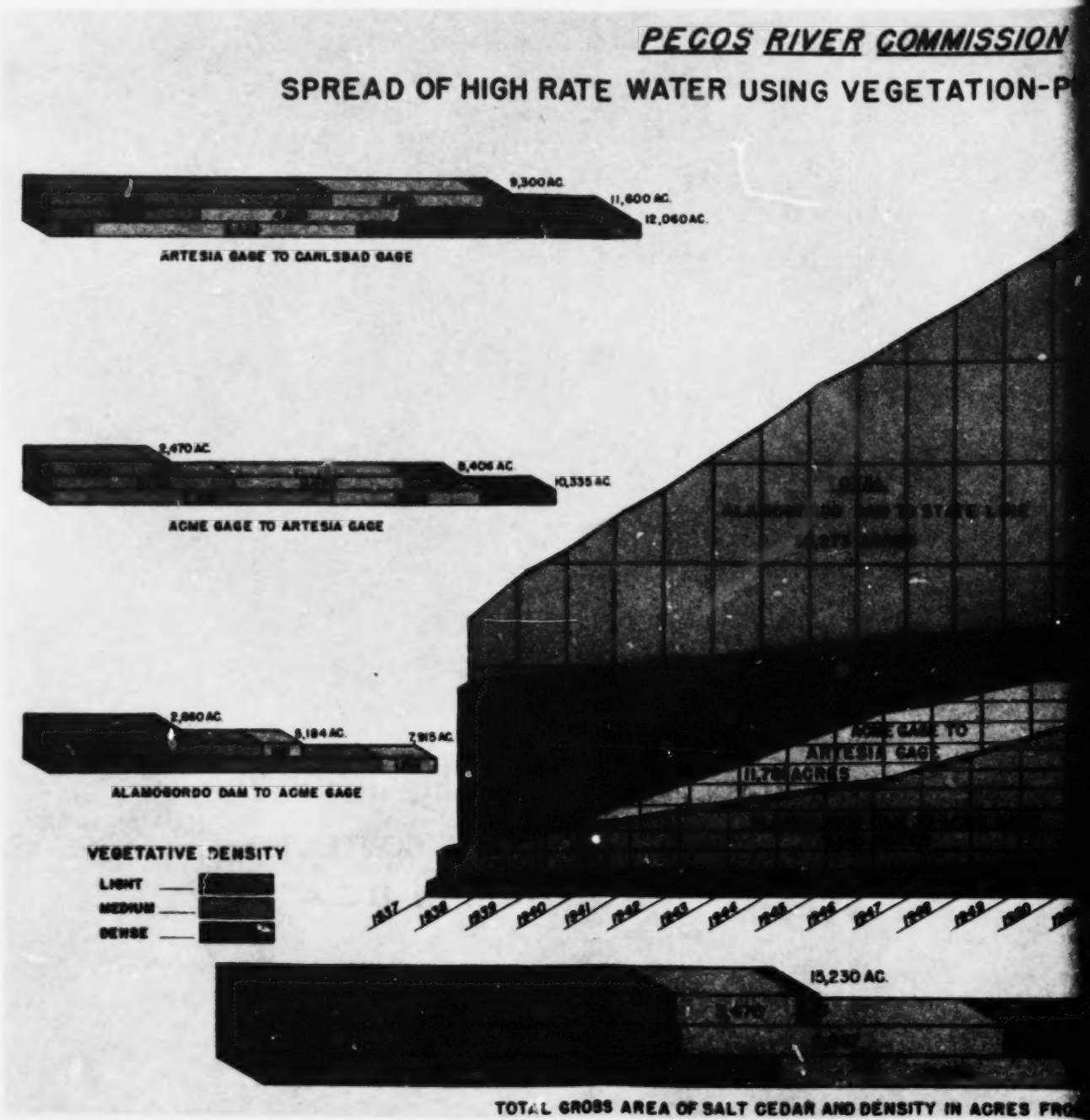

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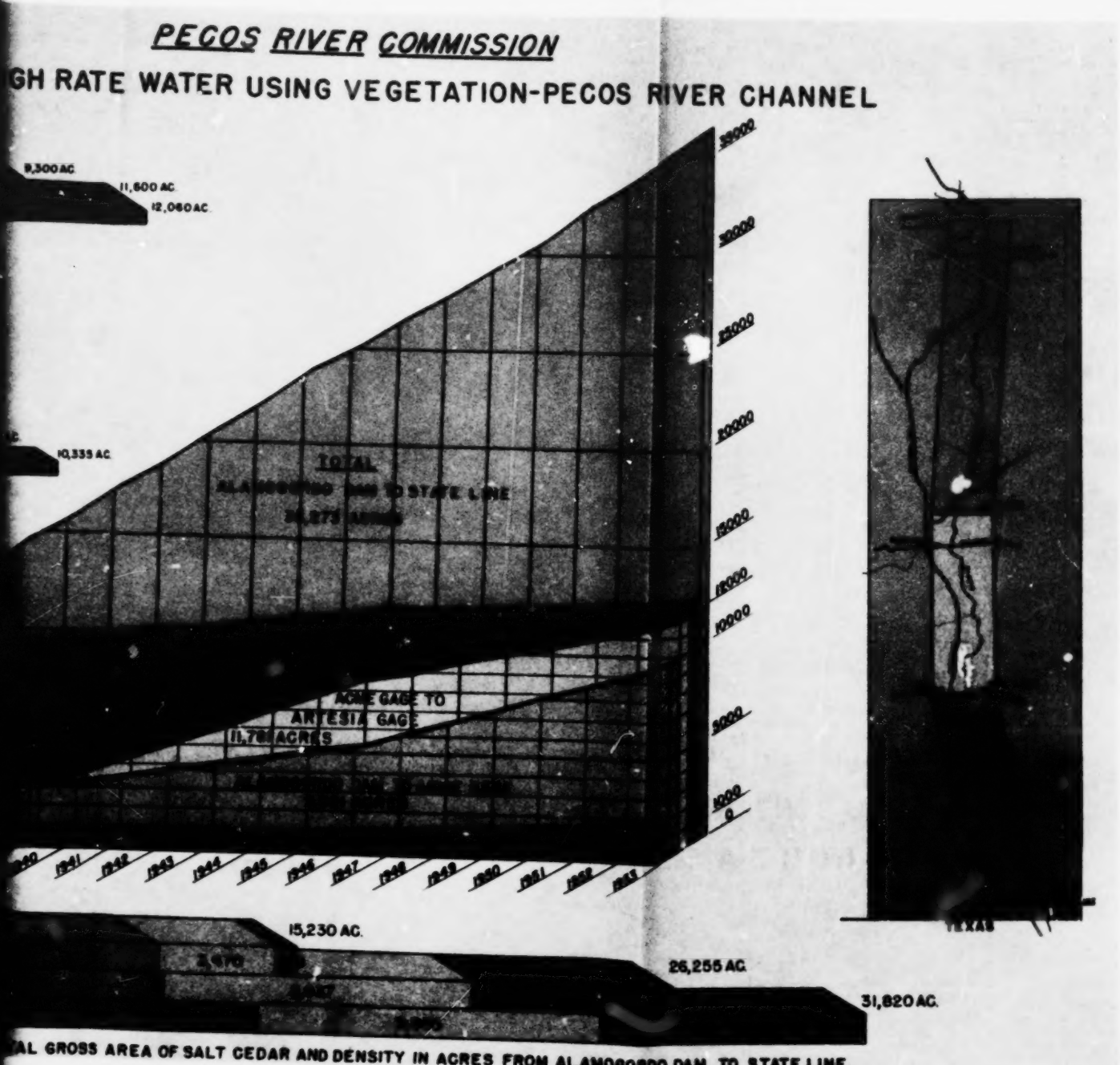
FIGURE 2.—Adapted from Pecos River Commission of New Mexico and Texas, 19

4-A



AL GROSS AREA OF SALT CEDAR AND DENSITY IN ACRES FROM ALAMOGORDO DAM TO STATE LINE.

FIGURE 2.—Adapted from Pecos River Commission of New Mexico and Texas, 1955.

4-A

TABLE 2.—*Area of phreatophytes and estimated annual use of water by them in river basin areas of Western United States*

[Compiled from reports of Federal and State agencies]

State and river or valley	Area in acres	Estimated annual water use in acre-feet	Year of survey or estimate	Principal species of phreatophytes
Arizona:				
Little Colorado River: [1]				
Main stem only St. Johns to mouth	49,560	64,720	1951	Saltcedar, cottonwood, willow, brush.
Total Little Colorado including Zuni and Puerco Rivers	65,310	74,360	1951	Do.
Gila River: [1]				
Virden, N. Mex. to Clifton, Ariz	5,600	6,310	1951	Cottonwood, willow, seepwillow.
Head of Safford Valley to Coolidge Dam	25,520	61,500	1951	Saltcedar, mesquite, willow, seepwillow, cottonwood, arrowweed.
Coolidge Dam to Kelvin	3,970	7,460	1951	Do.
Kelvin to Gillespie Dam downstream from Granite Reef Dam on Salt River, Rillito on Santa Cruz River and Lake Pleasant on Agua Fria River	142,880	282,770	1951	Do.
Gillespie Dam to Dome	51,270	69,220	1951	Saltcedar, mesquite, seepwillow.
Total Gila River including San Pedro River, Palominas to mouth, Verde River Bartlett Dam to mouth, Salt River, Stewart Mountain Dam to Granite Reef Dam	300,710	522,510	1951	
Salt River: [1] Stewart Mountain Dam to Granite Reef Dam	2,710	3,070	1951	Saltcedar, mesquite.
San Pedro River: [1] Palominas to Gila at mouth	42,510	69,420	1951	Do.
Verde River: [1] Bartlett to Gila at mouth	3,790	5,720	1951	Saltcedar, mesquite, seepwillow.
California:				
San Luis Rey River: [2] In San Diego County	6,390	17,800	1945	Cottonwood, willow.
Santa Ana River: [3] Below Prado Dam	1,071	3,000	1946	Do.
Kings River: [4] Kings River Soil Conservation District	1,080	[5] 6,500	1958	Do.
Idaho: Malad Valley [6]	10,900	32,400	1953	Grasses and rushes.
New Mexico:				
Pecos River: [7] [8] Alamogordo Dam to Texas State line	42,500	117,000	1956	Saltcedar.
Rio Grande: [8] [9] Bernardo to San Marcial	52,000	77,800	1955	Do.
Nevada:				
Little Humboldt River: [10] Paradise Valley	36,500	23,000	1947	Greasewood, saltgrass, willows.
Muddy River: [1] To mouth	4,900	10,330	1951	Saltcedar.
Nevada-Utah-Arizona-California:				
Virgin River: [1] Littlefield to mouth	7,360	27,160	1951	Do.
Lower Colorado River: [1]				
Main stem:				
Lee Ferry to Hoover Dam	1,480	5,920	1951	Saltcedar, willow.
Hoover Dam to Davis Dam	4,500	11,450	1951	Do.
Davis Dam to Parker Dam	57,490	209,290	1951	Do.
Parker Dam to Laguna Dam	191,890	314,360	1951	Do.
Laguna Dam to International Boundary	33,510	54,210	1951	Do.
Total main stem	288,920	595,230	1951	
Total Lower Colorado River Basin, including Little Colorado River, Virgin River, and Gila River Basins	667,200	1,230,090	1951	

[1] Bureau of Reclamation, table.
[2] Muckel, D. C., and Blaney, H. F., 1945.
[3] Muckel, D. C., and Blaney, H. F., 1946.
[4] Muckel, D. C., 1959.
[5] April to September, inclusive.
[6] Mower, R. W., and Nace, R. L., 1957.
[7] Pecos River Commission, New Mexico and Texas, 1955.
[8] Thompson, C. B., 1957 (a).
[9] Thompson, C. B., 1957 (b).
[10] Loeltz, O. J., Phoenix, D. A., and Robinson, T. W., 1949.

a result, the normally high sediment load of the floodwater is deposited in the area of phreatophyte infestation. Invasions of phreatophytes onto productive farm and rangelands decrease crop yields and increase cultural and maintenance costs.

The Corps of Engineers, as a result of their flood-control studies of the Gila River, have recommended the clearing of phreatophytes from a 2,000-foot-wide channel on the flood plain of the streams. A report by the Corps of Engineers (Newton, C. W., 1957) contains the estimates by the Bureau of Reclamation of the use and salvage of water in the 78-mile reach from Brown Canal heading at the upper end of Safford Valley to the San Carlos Reservoir. It was estimated that the use of water by phreatophytes on 11,200 acres to be cleared was 39,280 acre-feet a year. It was further estimated that water salvage resulting from the proposed clearing would average 28,100 acre-feet a year. Of this amount it was estimated 11,800 acre-feet would be lost in conveyance and that 16,300 acre-feet would be available at points of farm delivery.

The most comprehensive study of the use of water by phreatophytes in Safford Valley was made by the Geological Survey in 1943–45 (Gatewood, 1950). In the 46-mile reach of the valley from Thatcher to Calva at the head of San Carlos Reservoir, the use of ground water was estimated as 23,000 acre-feet a year.

In 1950, at the request of the Corps of Engineers, the Geological Survey (Turner, S. F., and Skibitzke, H. E., 1950) estimated the use of water by phre-

atophytes between Granite Reef Dam and Gillespie Dam on the lower Gila River. These estimates of water use, and of the saving that would result from clearing, were made for the conditions with and without Colorado River water introduced into the area. The estimated transpiration from ground water during the period 1950–99 without Colorado River water was 22,000 acre-feet per year, and with Colorado River water, beginning in 1960, was 30,000 acre-feet per year. The estimated water saving during this period was 16,000 acre-feet per year without the introduction of Colorado River water and 22,000 acre-feet per year with Colorado River water introduced in 1960—all of which would be available for beneficial use.

The Pecos River in New Mexico probably has the most serious water problem of any stream in the Southwest. The phenomenal increase in the area covered by saltcedar is shown in figure 2. During the course of the Pecos joint investigation, 1939–41 (National Resources Planning Board, 1942, p. 56), an analysis was made of the streamflow depletion by saltcedar above Lake McMillan for the period May 1934 to July 1940. The average yearly depletion during this 6-year period was 54,000 acre-feet. In 1939 the area of saltcedar was 15,200 acres, of which about 13,000 acres was concentrated in the delta of Lake McMillan. Here the conditions are ideal for dense and vigorous growth. As shown in table 2, Thompson (1957a) estimated the use of water by saltcedar in the reach from Alamogordo Dam to the Texas State line as 117,000 acre-feet per year. At the present time, 1959, it is estimated to be 125,000 acre-feet.

Owing to a peculiar condition that exists in the Pecos River, the waste of this water results in a twofold effect: first, by loss to irrigators and water users and, second, by a deterioration of the quality of the water in the main stem of the river below McMillan Dam and particularly in the vicinity of the Texas State line. Between 15 and 20 miles upstream from the State line, there is an inflow of highly saline ground water. This inflow adds to the river water about 420 tons of dissolved minerals daily, of which about 370 tons is common salt. The draft by saltcedar reduces the volume of streamflow and this in turn reduces the dilution of the salt-water inflow, resulting in saltier river water. During periods of low flow the salt content of the river water renders it unfit for irrigation.

Thompson (1957b) (table 2) estimated the use of water in the Rio Grande between Bernardo and San Marcial was 77,800 acre-feet in 1955. For the Rio Grande Basin in New Mexico, as a whole, it is not beyond the realm of possibility that in 1959 the use by phreatophytes will be on the order of 150,000 acre-feet.

The Bureau of Reclamation estimates the stream depletion of the main stem of the Colorado River below Lee Ferry as nearly 600,000 acre-feet a year (table 2) and for the entire basin below Lee Ferry at about twice this amount.

STATUS OF KNOWLEDGE AND NEED FOR FURTHER RESEARCH IN THE FIELD OF WATER USE BY SPECIES OF PHREATOPHYTES

Although limited general information concerning phreatophytes is greater than it was a decade ago, much more specific data relative to their growth habits, requirements, methods of control, etc., are required if the problems are to be adequately solved. The greatest advance has been made in identifying plants that occur as phreatophytes and in determining the annual use by the common species. Robinson (1958) lists 74 plants that have been identified as phreatophytes. Not all of these are problem plants, for some occur only locally, some are not excessive water users, and some, such as alfalfa, are valuable forage plants.

Although the plant species are rather well known, their distribution and especially their areal extent are largely a matter of conjecture. An attempt to show the distribution of a species—saltcedar—is shown on the accompanying map (fig. 1). Although the map is not complete it does portray the distribution of the plant. Similar maps in greater detail are needed for the rest of the common species. In this connection it should be noted that the States of Colorado and Utah are undertaking to map the area and distribution of phreatophytes in their respective States.

Information is available on the use of water by the common phreatophytes at one or more localities as shown in table 1. Much more information is needed not only for those shown but also for the threescore of other phreatophytes for which there are virtually no data on water use. It is known that the use of water varies with the species, with the depth to the water table, with density of growth, and with climate. Research is needed to relate all of these factors. An illustra-

tion of the effect of these factors is furnished by the range in water use by individual species and by the same species at different and at the same locations, as shown in table 1.

Information on the relation of phreatophyte species to the depth to the water table is scanty, and in some instances is conflicting. It is known that some phreatophytes such as saltcedar, mesquite, and alfalfa are deeprooted, and that saltgrass is shallow rooted, but there are hardly any data on the limit to which the roots will go in search of water. It has been inferred from observation that the use of ground water by most species decreases substantially beyond a depth of 7 feet, but there is little information to sustain this inference.

Very little is known about the quality of water preferred by most species of phreatophytes or the amount of dissolved solids they can tolerate. It is known that certain plants, such as pickleweed, have a high salt tolerance; others, like greasewood, saltcedar, and saltgrass are less tolerant; and some, such as willow, grow only where the ground water is low in dissolved salts. Also, very little is known of the effect of mineralized ground water on plant growth or the tolerance of any species for any particular mineral in the water.

With the exception of alfalfa, little is known of the economic or cultural value of most phreatophytes. It is known, however, that the wide range of adaptability and general characteristics of this plant group would indicate potential value which, under certain conditions, would appear to warrant their retention in spite of high water use. Some species are particularly valuable in streambank stabilization and other forms of water and wind erosion control. These same species along with others have esthetic values and provide food and cover for wildlife, thus establishing a favorable habitat in areas otherwise lacking these features. Others have limited value for lumber, forage, fiber, and other use. Research is needed to further determine these values in order that proper consideration can be given to their overall use.

In the field of ecology some knowledge has been gained in the past few years, but further research is needed on: methods of reducing or preventing propagation; seedling growth and development; depth of root activity and relation to the water table; factors that determine survival, aggressiveness, and rate of spread; and methods of evaluating density of growth. Methods of evaluating density have been under study by the Phreatophyte Subcommittee, Pacific Southwest Inter-Agency Committee, for the past 2 years. The study was the subject of a provisional report by a task force of the subcommittee in 1958 entitled, "A guide to the density survey of bottom land and streambank vegetation." A revision of this report, to be published in 1960, will describe improvements in methods and new methods of evaluating density.

Considerable advancement has been made in methods of eradication. The methods that appear to be most successful are mechanical (uprooting) and chemical (sprays). Burning, a third method, has not proved successful. When used in conjunction with other methods it may provide a cheap and rapid method of clearing old growth. At present the mechanical method is favored over the chemical method, largely because of the danger of the spray drifting to adjacent agricultural land and damaging crops thereon, especially when applied from airplanes. Once an area has been cleared mechanically, control of any regrowth and of new growth by spraying is quite effective. The Bureau of Reclamation and the Agricultural Research Service have for several years been making studies together of the effectiveness of different spray formulations, concentration, and time of application on saltcedar in Arizona. Much valuable information has resulted from these studies. There is also a possibility that biological control may some day play an important part in the management of areas so infested. Research of this nature for species other than saltcedar is needed.

Perhaps less is known about salvage and salvage methods than for any other phase of the phreatophyte problem. It is known that removal of vegetation adjacent to a stream will increase the flow of the stream. Very little data are available concerning the effectiveness of salvage methods such as: clearing of vegetation; lowering the ground-water level by pumping or drainage; substituting vegetation of a higher economic value for the existing low-value plants; lining stream channels to convey water through areas of transpiration discharge; and utilizing existing low-value phreatophytes so as to increase their economic value. Studies to date indicate that the replacement of the phreatophytes with desirable vegetation of a high economic value

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after the initial clearing is an effective maintenance procedure. It is also an economical method of channel and floodplain stabilization. Research is needed for all of these methods.

ACCOMPLISHMENTS IN THE FIELD OF PHREATOPHYTE CONTROL

Perhaps the largest phreatophyte control program has been conducted in the Rio Grande Valley in a cooperative venture by the State of New Mexico and the Bureau of Reclamation in their quest to save irrigation water so valuable to that part of the irrigated West.

In this valley lie the middle Rio Grande and the Rio Grande irrigation projects. In parts of this area the infestation of saltcedars and other phreatophytes is especially dense, resulting in large quantities of water being consumed nonbeneficially.

In the middle Rio Grande, water salvage work has consisted of constructing a low flow conveyance channel where necessary and a dyked floodway from 600 to 1,400 feet wide which will extend for about 217 miles when completed. A floodway is being cleared of phreatophytes to allow the flow of floodwaters and to reduce the transpiration losses. It is estimated that this program of taking the water away from the phreatophytes and taking the phreatophytes away from the water has resulted in the saving of 307,600 acre-feet of water between the years 1951 and 1958. When the present program is completed, it is estimated that over 50,000 acre-feet will be saved each year. Mechanical and chemical control methods were used principally in this area.

The Bureau of Indian Affairs is also using mechanical methods followed by chemical treatment to clear a sizable area along the upper Gila River in Arizona.

In the Caballo Reservoir area, Rio Grande project, the Bureau of Reclamation and the State of New Mexico removed 5,300 acres of phreatophytes, principally saltcedar and mesquite, by mechanical means. It is estimated that 14,000 acre-feet of water will be saved annually as a result of this undertaking.

The Bureau of Sport Fisheries and Wildlife has cleared mechanically several thousand acres of river-bottom vegetation, including saltcedar, willow, and cottonwood, on the Bosque del Apache National Wildlife Refuge. The saltcedar population varied from seedlings to trees up to 5 inches in diameter.

Despite the high cost, mechanical methods are being used on thousands of acres by the Bureau of Reclamation, the New Mexico State engineer's office, the U.S. Boundary Commission in New Mexico and Texas, and the U.S. Fish and Wildlife Service to control phreatophyte growth in strategic conveyance channels and floodways, on levees and canal banks, and on critical feed-producing areas in wildlife refuges.

Another large-scale phreatophyte clearing program has been on the Gila River, which runs some 70 miles through the full length of the Wellton-Mohawk division, Gila project, Arizona.

The Corps of Engineers is currently constructing Painted Rock Dam on the Gila River, just above the Wellton-Mohawk division. The dam will limit flood releases to 20,000 cubic feet per second. The corps is planning a channel to carry this flow on downstream to the Colorado River. On the basis of potential flood control alone, the Wellton-Mohawk Irrigation and Drainage District, as a part of its operation and maintenance program, contracted for clearing a 200-foot wide pilot channel the full 70-mile length of the project. They then widened this to a 400-foot flood channel.

The Bureau of Reclamation, the Wellton-Mohawk Irrigation and Drainage District, and the Corps of Engineers are financing a study being made by the University of Arizona which will include: an evaluation of the clearing work undertaken; an ecological study of plant succession following clearing; physiological, laboratory, and field studies as may be determined; and the effect of clearing phreatophytes upon the quality and quantity of ground-water supplies.

A series of experiments dealing with the control of saltcedar was initiated near Phoenix, Ariz., in 1951 by the Agricultural Research Service and the Bureau of Reclamation. Findings to date indicate that clearing mature saltcedar growth by mechanical methods and burning the crushed-down debris followed by chemical spraying of regrowth is the most effective and least expensive method of control now known; that of the several chemical formulations tested, some are more effective than others; that regrowth of saltcedar from crowns and roots after mechanical clearance and burning

can be expected within the first growing season; that applications of certain formulations on mature saltcedar or regrowth following mechanical clearance usually will cause defoliation and kill a high percentage of topgrowth, but seldom will reduce the stand significantly; that young saltcedar regrowth or seedlings are much more easily killed by chemical application than is growth a year or more old; that mature saltcedar or regrowth after mechanical clearance requires repeated applications over a period of 2 or more years; that applications of some chemicals in oil or oil-water emulsion when plants are dormant are effective but expensive and suitable only for small or widely scattered infestations of saltcedar.

The Bureau of Reclamation is also cooperating with the Agricultural Research Service in the Big Horn Basin, Wyo., and Salt River, Ariz., in ecological and control studies. These agencies are also cooperating in a study of the water consumption by phreatophytes and other riparian vegetation along the Santa Ynez River in California.

The Forest Service, in cooperation with the Arizona State University at Tempe, is conducting ecological and physiological studies. Similar studies are carried on by the Fort Hays Kansas State College at Hays, Kans., in cooperation with the Bureau of Reclamation. At Tempe the Forest Service has also made considerable progress in the development of an infrared gas analyzer for measuring water vapor changes and its adaptation to measuring evapotranspiration losses.

The Geological Survey, the New Mexico State engineer's office, and the Pecos River Commission are investigating the use of water by saltcedar in the Pecos River Valley. The survey has also made extensive investigations on the use of water by bottom-land vegetation in the Safford Valley, Ariz.

The Soil Conservation Service began an intensive study in 1946 of the water requirements of native vegetation in several locations in Utah. This research, involving phreatophytes grown in tanks, was taken over by the Agricultural Research Service in 1956.

The University of Arizona has made some preliminary studies on biological control of saltcedar. The Agricultural Research Service is considering placing saltcedar on the list of introduced plants whose natural enemies will be studied in their foreign habitats.

Carbohydrate root reserve studies have been made cooperatively by the Agricultural Research Service and the Bureau of Reclamation in the Weed Control Laboratory at Denver, Colo.

The preliminary construction for one of the latest tests to determine consumptive use of saltcedar is just being completed. This cooperative project by the Geological Survey and the Bureau of Reclamation is located in the Salt River Valley west of Phoenix, Ariz. The latest instruments will be used in recording temperature, humidity, rainfall, wind velocity, depth to water table, soil moisture content, and other data for determining the consumptive use of the saltcedar.

Several studies are currently underway to find adaptable lower water consuming economic plants to replace phreatophytic growths. Some studies of this kind have been started at McMillan Reservoir, N. Mex. Work being done by the Agricultural Research Service and several State colleges is aiding also in the solution of this problem. In New Mexico the Bureau of Sport Fisheries and Wildlife is experimenting with pasture and other agricultural crops as replacement vegetation. In Oklahoma replacement of willow growth with wild millet and other plants has resulted in improved wildlife habitat.

The State of Nevada, Agricultural Research Service, and the Geological Survey are carrying out studies on the floodplain of the Humbolt River, Nev., to determine the evapo-transpiration rates of various phreatophytic plants.

Arizona State University in cooperation with the Phreatophyte Subcommittee of the Pacific Southwest Inter-Agency Committee and the various Federal and State agencies concerned have established a Phreatophyte Library at Tempe, Ariz. The library will serve as a depository for summaries of activities and findings of all groups working on the problem.

No doubt, many other agencies and organizations are working on such problems as developing effective herbicides, consumptive use of water, control measures, ecological studies, biological control, etc. All are anxious that the research work be continued for developing more economical and effective control methods, both mechanical

and chemical. More work is needed on biological control. In order to aid in the finding of better control methods, there is a need for more basic ecological studies to learn more about growth, reproduction habits, and soil, moisture, and climatic requirements.

We need to learn more about the actual amount of water used by various species of phreatophytes under different conditions of soil, moisture, and climate. It is also desirable to determine how much of the water saved through the elimination of phreatophytes can be salvaged and put to use.

COST OF ERADICATION

The cost of eradicating phreatophytes ranges rather widely, depending on the species of plants, the method and equipment used, and character of the terrain, and the size and density of the plants. Table 3, which has been compiled from actual cost data from clearing projects by Federal and by State agencies, illustrates the range in cost. The costs shown in the table are for uprooting or spraying only. It does not include disposal of the debris which generally is a part of any clearing project.

In their proposed clearing of the 2,000-foot floodway in the Safford Valley, the Corps of Engineers (Newton, C. T., 1957) estimated the cost of clearing 14,285 acres as follows: $100 an acre for dense growth (80 to 100 percent density); $60 an acre for sparse growth (less than 80 percent density). The area of dense growth was estimated as 7,665 acres and that of sparse growth as 6,620 acres.

Unless the land cleared is put to some agricultural use, there arises the problem of maintenance—to control regrowth and new growth. The cost per acre on an annual basis is less than for the initial clearing, as shown by costs of the International Boundary and Water Commission ($7.43), and the Bureau of Reclamation ($6.76), in table 3.

TABLE 3.—*Cost of eradicating phreatophytes from bottom land at various locations under different conditions of growth and treatment*

[Type of treatment: M=mechanical; S=chemical spray]

Agency	Location of project	Acres cleared	Cost per acre	Treatment	Equipment and remarks
International Boundary and Water Commission	Lower Rio Grande	40.5	$106.12	S	Ground spray on river bank.
Do	do	8,661	7.43	M	Mowing regrowth on floodways and levees.
State of New Mexico	Rio Grande Valley	4,741	11.19	M	D-8 tractor and disc.
Do	do	7,665	11.45	M	Do.
Do	do	4,500	9.27	S	Aerial spray, 3 applications.
Bureau of Reclamation	Rio Grande-Caballo Reservoir area	883	11.29	M	TD-24 tractor and rock rake
Do	do	553	21.55	M	D-8 tractor and rock rake.
Do	do	305	12.66	M	TD-18 tractor and dozer blade.
Do	do	1,123	5.35	M	Farm tractor and rotary brush cutter; light growth.
Do	do	480	6.76	M	Ground spray on regrowth.
Do	Middle Rio Grande	6,000	60.00	M	Clearing floodways.
Fish and Wildlife Service	Rio Grande-Bosque del Apache	4,500	19.00 3.03	M	Tractor-dozer blade, dense growth. Tractor brush cutter, medium growth.
Do	Pecos River Valley	350	2.69 35.00	M	Tractor disc, light growth.
Wellton-Mohawk Irrigation and Drainage District	Lower Gila River		[1] 30.00	M	Density 80 to 90 percent, undercutting only.
Do	do		[1] 15.00	M	Density 60 to 70 percent, undercutting only.
Do	do		[1] 10.00	M	Density 40 to 50 percent, undercutting only.
Do	do		[1] 6.00	M	Density 20 to 30 percent, undercutting only.

[1] Additional cost of raking and piling debris is about $10 per acre.

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3. Life History of Saltcedar. Transactions of the Kansas Academy of Science, vol. 60, No. 4, 1957
4. Symposium on Phreatophytes—Phreatophyte subcommittee, Pacific Southwest Inter-Agency Committee
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6. Tamarisk, History-Studies-Control—Bureau of Reclamation, U.S. Department of the Interior
7. Saltcedar Control with Chemicals—Agricultural Research Service, U.S. Department of Agriculture
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9. Carbohydrate Reserves in Tamarisk—Bureau of Reclamation, U.S. Department of the Interior
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PART II

VEGETATION MANAGEMENT AND WATER YIELDS IN THE 17 WESTERN STATES

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COMMUNICATIONS

U.S. SENATE,
SELECT COMMITTEE ON NATIONAL WATER RESOURCES,
July 13, 1959.

Hon. EZRA TAFT BENSON,
The Secretary of Agriculture,
Department of Agriculture, Washington, D.C.

MY DEAR MR. SECRETARY: Reference is again made to my letter of June 15, concerning the work of the Select Committee on National Water Resources. Among other aspects of the water resources field to which the attention of the committee is directed by Senate Resolution 48, is reduction of evapotranspiration as a means of increasing the usefulness of available water resources. The committee believes that agencies of the Department of Agriculture are well qualified to provide necessary background for the committee's studies in this field. Accordingly, it is requested that a report on vegetational management as a means of increasing water yield be prepared for the committee by the Department.

Principal objective of the report should be to furnish background for the committee to use in considering steps that might be taken to encourage developments in this field. The report should contain a description of the relation of various types of watershed vegetative cover to water yield together with information on the density and types of cover favoring maximum water yields for major types of watersheds in the 17 Western States. Insofar as it is available the report should contain benefit-cost relationships of vegetative management practices to increase water yield in the 17 Western States.

The report should also contain a summary and evaluation of present programs of research on management of vegetation for improving water yield including programs carried out by other Federal agencies and by non-Federal interests. The report should conclude with the Department's recommendations for future research and developmental work in this field.

We would like this subject to be covered in a summary report of not more than 10,000 words with whatever charts, tables, appendixes, and graphic illustrations as may be considered necessary. It would be most helpful if this information could be furnished the committee by October 15, 1959.

The committee staff will be glad to discuss any problems which may arise in the preparation of the report with representatives of the Department of Agriculture.

Sincerely yours,

ROB'T S. KERR, *Chairman.*

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DEPARTMENT OF AGRICULTURE,
Washington, D.C., January 28, 1960.

Hon. ROBERT S. KERR,
Chairman, Select Committee on National Water Resources,
U.S. Senate

DEAR SENATOR KERR: In response to your letter of July 13, 1959, the U.S. Department of Agriculture has prepared this report on vegetation management as a means of increasing water yields in the 17 Western States. Three other reports to the committee cover the probable future supplies and demands for water by agriculture and the needs for water resources research.

Emphasis is given in the report to those vegetation types where, based on present knowledge, opportunities for improving water yields appear best. More information is available on the management of vegetation and its effect on water yield in some areas than in others. We hope to continue accumulating our knowledge through an expanding physical and economic research program.

In this report we have considered other uses of the land for timber, forage for livestock and game, recreation, and agricultural production, as well as water, and have pointed out the effects of a program for increasing water yield on these uses. We feel strongly that no program which will damage or destroy the basic soil resource is justified. Furthermore, there are inadequate economic data and analysis techniques available at this time upon which to base decisions of using lands for water yield as against other uses.

Nevertheless, despite inadequate information, decisions with respect to use of land for water or for other resources must continually be made by the Department in connection with its administration of the national forests and other public lands under its jurisdiction. In consideration of these multiple-use problems, the Department considers not only the technical aspects of land management, but also the economic and other implications of its actions on dependent communities and populations. In the section of the report dealing with "Application Requirements and Limitations" there is a brief statement of the policy now being followed in regard to improvement of water yields from the national forests.

Your letter asked for benefit-cost relationships of vegetation management practices, insofar as available. The physical research is just getting well started and there has been no economics research done by the Department of Agriculture on the specific subject of water yield. We regret not being able to furnish such information.

We appreciate the privilege of preparing this report on vegetation management and water yields for your committee. We shall be glad to meet with your committee or your staff to discuss the subject further, if you desire.

Sincerely yours,

E. L. PETERSON, *Assistant Secretary.*

PART II

VEGETATION MANAGEMENT AND WATER YIELDS IN THE 17 WESTERN STATES [1]

HIGHLIGHTS

Opportunities for improving water yields through management of vegetation appear favorable on about 15 percent of the area of the 17 Western States west of the 100th meridian, particularly in the forested and higher elevation zones. In most circumstances, other resources of the land are involved and consideration must be given to their management and sustained production, as well as water. On this basis, estimates of water yield improvement opportunities from broad groupings of vegetation types of the West have been made. These estimates are yields at point of origin on treated areas immediately following treatment and not at some other point downstream. No assumptions are made as to how much of each vegetation type will be treated or of the acre-feet of water yield increase.

1. Forests in the snowpack zone hold the best opportunities for improved water yields through vegetation management. Precipitation ranges from 20 to 100 inches annually, averaging 40 to 50 inches. Roughly, 20 inches or 45 percent of this precipitation normally appears as runoff. Preliminary studies of cutting patterns and other forest management practices which reduce interception and evaporation losses and increase the snowpack indicate possible increases in water yield as much as 4 inches (20 percent). However, markets for the forest products and access roads to the forest areas will need to be developed before these areas can be extensively treated.

2. The Douglas-fir, hemlock, redwood forests of the North Pacific slope, make up a 25-million-acre area where water yield is less of a problem than is flood prevention and preservation of water quality. Opportunities for improving water yields appear abundant should a need arise in the future.

3. The interior ponderosa pine and Douglas-fir types together occupy 43 million acres of middle elevation lands which are important not only for yield of water but also for timber production, recreation, and grazing for livestock and game. These lands yield an estimated average of 4 inches of water, about 20 percent of the average annual precipitation. Although several different treatments might be applied to these forests to improve water yields, no experimental work has been done. It appears, however, that the present forestry practices of thinning in dense young stands and individual tree or group selection cutting in sawtimber stands will yield the greatest amount of usable water. It is estimated that careful management could result in increases in water yields of 0.5 to 1 inch, annually, over that from unmanaged stands.

4. The chaparral and woodlands are estimated to yield an average of 7 inches in central California 5 inches in southern California, and 1.5 inches in Arizona. In central California, this amounts to 28 percent of the precipitation but only 8 percent in Arizona. The best opportunities for increasing water yield appear in converting some of these brushlands to grass. Approximately 50 percent of the chaparral and woodlands may be suited to this treatment, and it is estimated that increases of 0.5 to 1 inch would result.

5. The piñon-juniper type occupies areas of low precipitation (15 inches average annual) with only 0.5 inch of water yield. Juniper control and conversion to grass may result in an increase of 0.25 inch in water yield, but this seems possible on only 10 percent of the area. Improvement of piñon-juniper lands for increased forage is recommended.

6. The semiarid grass and shrub is generally a sparse, low-growing vegetation occurring in areas with an average precipitation of 12 inches. Only

[1] Includes only that area roughly lying west of the 100th meridian in that area commonly referred to as the 17 Western States, excluding Alaska and Hawaii.

3.5 percent of the precipitation, 0.4 inch, is currently being yielded and the opportunities for increasing this yield are small. Increased efficiency of water use together with better control of erosion through improved range forage production offers the best course of action.

7. Phreatophytes and other riparian vegetation use an estimated 25 million acre-feet of water annually. A saving of 25 percent of this water appears possible by converting the high water-using vegetation to a vegetation using less water or by diverting water away from phreatophyte areas. This amounts to 6 million acre-feet or 1.4 percent of the total annual water yield from the 17 Western States.

8. Water from the alpine zone is almost entirely from snowmelt. High winds move snow into deep drifts behind natural barriers. Supplementing the natural barriers with artificial barriers will increase drifting which may result in an extension of the melting period later into the summer months when water is in greatest demand for downstream uses.

Programs of vegetation management to increase water yields will have greatest significance in local tributary watersheds rather than in large river basins. Areas to be treated should be carefully and wisely selected and treatments applied on the basis of good forestry and range management. Management practices which will give protection to the watershed and insure high-quality water deserve emphasis.

INTRODUCTION

Since the beginning of settlement, water has been a governing factor in the development of the West. As populations, industry, and agriculture continue to expand, limitations imposed by water scarcity are more and more sharply felt. On the other hand, total annual average yield of water from lands in the 17 Western States is in the magnitude of 440 million acre-feet (1)[2] or about 25 percent of the total precipitation. The water problem in the West is not entirely one of total water supply but also there are problems of distribution of supply, availability at a time when most needed, quality control, and losses of water through inefficiencies of use and through consumption by low-value vegetation.

This report presents an analysis of the opportunities for improving water yields through vegetation management. Water yields are considered as at the point of origin, measured immediately below treatment areas and not as quantities of water delivered to the point of use. Waters available at the point of use have been subjected to transmission and other losses which are not accounted for in this report but are considered in another report to the select committee, "Estimated Water Requirements for Agricultural Purposes and Their Effect on Water Supplies in the Years 1980 and 2000."

[2] Numbers in parentheses refer to references listed at the end of this report.

TABLE 1.—*Comparison of area, precipitation, and present and potential water yield for some vegetation types of the West*

Vegetation type	Area	Range in precipitation	Present water yield			Potential increase in yield		
			Range	Average	Percent of precipitation	Average [1]	Percent of present [1]	Percent of Area treatable
	Thousand acres	*Inches*	*Inches*	*Inches*		*Inches*		
Forest:								
Lodgepole pine	[3] 14,470	20-45	6-30	14.0	42.0	3.0	21.0	70.0
Engelmann spruce-fir	[3] 7,400	20-45	8-40	18.0	54.0	3.0	16.0	70.0
White pine-larch-fir	[3] 6,900	24-60	5-40	20.0	48.0	4.5	22.0	65.0
Mixed conifer [4]	[3] 8,470	17-70	1-50	22.0	50.0	4.5	20.0	65.0
True fir	[3] 6,150	40-100	20-60	36.0	60.0	6.0	17.0	60.0
Aspen	4,000	20-45	1-20	10.0	30.0	3.0	30.0	70.0
Pacific Douglas-fir-hemlock-redwood	[3] 25,570	20-100	10-80	45.0	60.0	[5]	[5]	[5]
Interior ponderosa pine	[3] 34,200	20-30	0.5-15	4.0	19.0	.5	5.2	65.0
Interior Douglas-fir	[3] 9,000	22-35	1-20	7.0	25.0	1.0	14.0	70.0
Chaparral and woodland:								
Southern California chaparral	7,500	12-40	0-20	5.0	20.0	1.0	20.0	50.0
California woodland-grass	9,000	12-40	0-25	7.0	28.0	1.0	14.0	
Arizona chaparral	5,500	12-25	0-5	1.5	8.0	.5	33.0	
Piñon-juniper	61,400	10-20	0-3	.5	3.3	.25	50.0	10.0
Semiarid grass and shrub	330,000	5-20	0.1-1	.4	3.5	0	0	
Phreatophytes	16,000						25.0	
Alpine	10,000	25-80	15-65	32.0	62.0	[6] 0	0	

[1] Initial increase on area treated only. The reader is cautioned to read the section on application requirements and limitations before attempting to calculate acre-feet of increase for a vegetation type.
[2] Commercial forest land area which is (*a*) capable of producing usable crops of wood, (*b*) economically available now or prospectively, and (*c*) not withdrawn from timber utilization.
[3] Mixed conifer type includes the California west side pine, pine-fir and white pine of western Oregon and Washington.
[4] No increases in total yield expected but better seasonal yield.
[5] Opportunities for improving water yields appear to be abundant.

In large part this report deals with lands undeveloped for crop agriculture. This is because forests, ranges, and rough unproductive areas make up most of the Western States and some of these areas are the primary water source areas of the West. On croplands, both irrigated and nonirrigated, the interest of agriculture is in holding water on the land where it falls and in improving efficiency of use of this water through improved crops and moisture conservation practices. Those areas located east of the shortgrass plains are not considered in the report.

The major source areas of water in the West for municipalities, agriculture, and industry are the forested and associated lands lying at the higher elevations. Opportunities for physically improving water yields from these areas appear favorable. However, those lands which lie below the forest zone in mountainous areas and farm and rangelands east of the Rocky Mountains in the Great Plains are also important sources of water. In fact, many of the lands of the West except the desert and semidesert possess some potential for improved water yields, but efficient use of water where it falls may be the most economic practice in some cases.

The role of vegetation in improving water yields

Vegetation is one of the most important factors that influence the amount and quality of water yielded from a watershed at a given time. Large amounts of precipitation generally produce dense stands of vegetation, whereas dry climates produce sparse vegetation. Except as precipitation may be altered through the application of present and future scientific discoveries and as snow accumulation and melt in the alpine regions above timber line are artificially controlled, amount and kind of vegetation are the only factors readily changed through management. It is the combination of vegetation with soils, climate, geology, and topography that determines water yields, so in order to improve water yields from watersheds an understanding of the interactions of these factors is important.

The influence of vegetation on movement of water through the hydrologic cycle includes (*a*) interception of precipitation in the foliage and branches; (*b*) infiltration and percolation of water into and through the soil; (*c*) transpiration or use of soil water by the vegetation itself; and (*d*) evaporation of moisture from the surfaces of the vegetation and the ground.

Interception.—The first point of vegetation control of water movement is when precipitation strikes the vegetation. Precipitation may be retained in foliage and evaporated; it may temporarily collect on leaves or needles, then drip to the ground; or it may run down stems and accumulate in a small area at the base. Precipitation caught in foliage and evaporated contributes nothing to water yields. The amount intercepted depends largely upon intensity, amount, and kind of precipitation and the density, type and height of vegetation. A smaller proportion of a heavy rain is intercepted than of a light shower. Snow is more readily held than is rain or other precipitation. Interception differs for grass, shrubs, trees or combinations of these. Also whether plants are conifers or broad-leaved, evergreen or deciduous, have large or small crowns, short or long branches, rough or smooth bark, influences interception. Vegetation management to increase water yields will aim to reduce interception.

Infiltration and percolation.—Precipitation reaching the ground may be evaporated from the surface of the soil, it may run off the surface, or it may enter the soil to be used by vegetation or to drain into streams, springs or underground aquifers. The process of water entering the soil is called infiltration, and the movement of water to deeper depths in the soil is called percolation. Water entering the soil first replenishes moisture deficiencies and raises soil moisture to field capacity, and then contributes to streamflow and ground-water supplies.

Infiltration is determined by conditions at the immediate soil surface, whereas percolation is controlled by subsurface conditions. Soils having coarse texture or of large aggregates, a layer of litter and humus on the surface, insects and small animals working in the soil and abundant roots of vegetation to make spaces for water movement and storage have high infiltration and percolation rates. Water in large pore spaces of the soil si held only temporarily, but this may be important in preventing rapid runoff of water during storm periods. Ultimately, soil water drains to lower depths or is withdrawn by evaporation, transpiration, or lateral flow.

Transpiration.—Transpiration or use of moisture by vegetation is also subject to control

through vegetation management. Some species of plants are physiologically adapted to transpire less water than other species either through less leaf surface or through control mechanisms.

In areas where seasonal drought is usual, the amount of water removed from the soil by transpiring plants depends largely upon the depth of root penetration. Therefore, opportunities for increasing water yields through vegetation management depend in part on the possibilities of reducing the amount of vegetation using water and changing the vegetation to a lower water-consuming type.

Evaporation.—Transpiration is only one part of the total evaporative loss that takes place in a watershed; water is also lost from ground and water surfaces. Amounts of water lost through evaporation depend upon the amount of energy striking the evaporating surfaces and upon the availability of water to be evaporated. In most parts of the Western States the energy to evaporate water far exceeds the amount of water available for evaporation and if water yields are to be improved through management of vegetation, that water must either be channeled deep in the soil beyond the reach of evaporative forces and the roots of transpiring plants or accumulated in deep reservoirs.

Other factors related to water yield

Water yield is influenced by many factors other than vegetation, and although they may not be subject to change they should be included in considerations of water yield improvement.

A broad relationship exists between geology and soils and the kind of vegetation they produce, but a given kind of vegetation may grow on a wide variety of soils and parent geologic materials and must be treated differently. Soils that are highly erodible, for example, must be carefully guarded when major vegetation changes are undertaken. It is essential that water be clean and usable and the soil mantle kept in a stable condition.

In some instances water control may be more important than increased yields, especially where flood prevention or reduction is an objective. Flood reduction is aided by detention of runoff and evapo-transpiration of antecedent moisture in the watershed, while maximum water yields may be enhanced by a decrease in the retention and consumption of water in the watershed.

The high mountain areas above the zone of tree growth are important water yielding areas because of their accumulation of deep snowdrifts during winter months and their feeding of the mountain streams in late spring and early summer. Improving seasonal water yield from these snowfields appears possible through controlling, by artificial means, the accumulation and melt of snowdrifts to prolong the runoff as late into the summer as possible.

Relation of water to other land uses

This report considers the possibilities of water yield improvement with water production as the highest priority use of the lands being discussed. However, there are other important considerations such as soil, timber, forage, wildlife, recreation, and agricultural crops which cannot be entirely sacrificed in favor of water yields. Efforts to increase water yields through vegetation management must consider other uses of the land and the Nation's growing need for these other resources. The principles of multiple-use should be followed, wherever possible. Opportunities and benefits of increasing water yields will be greatest to local areas.

In considering possible vegetation manipulation to influence water yield, institutional arrangements under which land is controlled or managed are often as important or sometimes more important in determining action than the physical characteristics of the land. It would be incompatible with certain institutional arrangements such as parks, recreational and wilderness areas to manipulate vegetation for purposes of water yield. However, the statistics used in this report are largely limited to those acreages which are not subject to such institutional restrictions.

Sites best suited for growing timber or grass are often the best water yielding areas, but these products require some of the water for their own growth and development. Livestock and game require drinking water. To grow the forage upon which they feed also requires water. On the other hand, demands for irrigation, municipal, and industrial uses are generally downstream and require storage facilities for efficient yearlong use of water supplies. Recreationists demand water

all along the way from snowfields to reservoirs. These demands at different points in the watershed will need to be reconciled as programs of water yield improvement develop.

For reasons of expediency, rather broad groupings have been made of the vegetation types of the West. This is especially true of the semiarid grass and shrub and the chaparral and woodland types, but hydrologically and from the standpoint of water yield problems, the groupings are considered similar enough to discuss as single units. Other groupings include (*a*) piñon-juniper, (*b*) forests below the snow zone, (*c*) forests in the snow zone, (*d*) phreatophytes, and (*e*) alpine.

Status of knowledge

Examples are abundant in the West where destruction of the vegetation cover on watersheds by overgrazing, logging, wildfires or poor farming practices have resulted in excessive runoff, erosion and floods. There are a number of experiences in rehabilitation of deteriorated watersheds through reestablishment of vegetation cover which demonstrate that vegetation is effective in controlling, in part, the water falling on a watershed.

The first studies of water yields in relation to vegetation management were begun in 1909 at Wagon Wheel Gap in the headwaters of the Rio Grande by the Forest Service and the Weather Bureau (2), but these studies were soon terminated and it is only recently that such research has been expanded significantly. Some examples of subjects of current water yield research in Western United States are as follows:

1. Patterns of cutting in spruce, fir and lodgepole pine in Colorado.
2. Comparisons of water consumption by trees, grass, and brush in southern California.
3. Clearing of woody streamside vegetation in chaparral-covered watersheds in southern California.
4. Ecological, chemical and mechanical control of saltcedar in Arizona.
5. Thinning of dense stands of ponderosa pine in Arizona.
6. Eradication of juniper and piñon species from grasslands used for grazing in Arizona.
7. Determination of the effect of grazing practices on runoff and sediment yields in Arizona, Colorado, and Oregon.

There are a number of other research projects that are supplying information in a direct or auxiliary way on the relationships between vegetation and water yields, but these too are only beginining to produce results. A considerable fund of knowledge has already been built up on physical relationships, but there are several fields where serious shortages of information exist: (*a*) the practical application of vegetation treatments for water yields on watersheds and the effects on other resources; (*b*) a thorough understanding of the basic processes and factors involved in improving water yields through vegetation management; and (*c*) the economics of watershed management for improved water yield.

To more fully appraise the opportunities to increase water yields and to apply the best management, there is a great need to expand the hydrometeorologic network to furnish climatic and streamflow data for the remote areas which yield much of the water of the West.

It should be understood that the estimates of increases in water yields which may result from vegetation management have a much more firm basis in some vegetation types than in others. They are based on the best information available at this time, but in some types the information comes from observation or deduction only and not from organized study.

FOREST LANDS (GENERAL)

Forests occupy important water-yielding areas characterized by higher elevations and considerable rain and snowfall. Because forest types delineate areas characterized by different elevations, climates and potentials for water yield improvement, several of the important ones will be discussed separately. They do, however, occur under a rather wide variety of environments, and hydrologically further separations are necessary, particularly in the ponderosa pine and Douglas fir in the interior and on the Pacific slope.

FORESTS IN THE SNOWPACK ZONE

Forests in the snowpack zone hold the best opportunities in the West for improved water yields through vegetation management. The snowpack zone lies above the interior ponderosa pine and Douglas-fir forests of the Rocky Moun-

tains (fig. 1) and along the crest and west slope of the Sierra Nevada and Cascade Ranges (fig. 2). Precipitation is heavy, 20 to 100 inches, and snow accumulates to great depths during the long cold winters. Snowmelt during spring and early summer supplies almost all the streamflow.

Typical of this zone in the Rocky Mountains are Engelmann spruce-fir, lodgepole pine, larch-fir-pine, and aspen, and in the Sierras and Cascades the typical forest is mixed conifers or nearly pure stands of true firs. Forest cover is dense. Total acreage of commercial coniferous forest in this zone is 43.6 million acres and there is an estimated 4 million acres of aspen (table 1). One-half to three-fourths of the acreage of each type is in sawlog or pole-size trees and the demand for lumber and wood products from this zone is increasing.

Recreational opportunities, hunting, fishing, hiking, camping, picnicking, and pack trips attract more people each year and this zone is the center of winter sports activities. Livestock grazing is important on the intermingled open lands, but most of the forest except aspen is too

dense for forage production. Aspen forests support a lush ground cover and are especially significant as food and cover for deer and elk.

Normal water yield

Water yield from snowpack forests is a major supply for western farms and cities. Average yield from this zone is estimated to be 20 inches but ranges from 10 inches for aspen to 36 inches for the true fir stands.

In the Sierras two-thirds to four-fifths of the runoff occurs during April, May, and June, while May, June, and July are months of greatest streamflow in the central and northern Rockies. Such late spring and early summer delivery is a great asset in meeting irrigation and other demands and minimizing the need for storage. Water from snowmelt is of high quality with little sediment or dissolved salts.

Possibilities for improving water yield

Opportunities for improving water yields from these snowpack forest areas seem to be considerable, by arranging cutting patterns and the structure of the forest in ways which will encourage maximum snow accumulation, minimum inter-

Figure 2

VEGETATION TYPES
17 WESTERN STATES

ception and evaporation of precipitation, and slow melting of accumulated snow. Fortunately, some tests have been made which indicate the possibilities in several different forest types.

In Colorado, a series of plot studies in lodgepole pine showed that removal of 25 percent of the timber volume increased the water content of the snowpack by 8 percent, 50 percent cutting gave a 15-percent increase, and commercial clear-cutting gave an increase of 30 percent over uncut stands. Thinnings in small pole-size stands gave about 20 percent more snow water. These results were applied to a 700-acre experimental watershed covered with lodgepole pine and spruce where about 40 percent of the trees were cut from the area in a checkerboard pattern alternating clear-cut with uncut blocks. Flow has been increased an average of 3.3 inches (about 25 percent) for the 3 years since cutting was finished. The increase was greatest the first year after cutting and it is not yet certain whether this increase will be sustained or will decrease with time. Furthermore, the spring peak flow has varied, being 50 percent greater in one year and 23 percent lower in another. Time and further study will clarify the results.

New studies in true fir forests of California show that interception and evapotranspiration losses were 8.6 inches less on cut strips, 6.3 inches less in larger block cuts, and 3.4 inches less in selectively cut stands than in adjacent unlogged areas. Such savings will normally be available as increased water yield.

These tests indicate that most of the increased yield would be obtained during the spring high-water period and storage is essential for maximum benefit. In some parts of the West storage is available, and increased water at any season can be put to good use. Elsewhere increases during the high-water period may be useless or detrimental, and this must be kept in mind in extending logging to the high mountain forests.

The amount of snow intercepted by forest cover increases with density of foliage and tree height. Maximum snow accumulation is found in openings no larger across than 2 to 10 times tree height. Aspen has the least interception because it loses its leaves in winter. Maximum yield is favored by narrow strips of forest surrounding openings perhaps 2 to 5 times as wide as tree height. Larger openings favor high evaporation rates. Late season yields will be increased by smaller openings, one to 1½ times tree height, so that the openings will be shaded. Different kinds of cutting systems will be needed for the various kinds of forests, slopes, and aspects, as well as to suit different demands on watersheds.

Two important noncommercial forest types in the snowpack zone are spruce-foxtail pine-mountain hemlock of timberline and aspen. The timberline transition forest plays an important role in snow accumulation and stabilizing avalanches because they are often arranged in an efficient pattern for trapping snow blown off the bare areas above them. The drifts thus formed melt slowly and feed late season flow. There are many opportunities to increase this effect.

The role of aspen in watershed management has conflicting aspects. Interception of snow under aspen trees tend to develop a fertile soil with high infiltration rates. On the other hand, aspen seems to use large amounts of water itself during the growing season. Removal of aspen from plots in Utah resulted in 3 inches more water left in the soil at the end of the growing season. Comparisons of soil moisture under aspen, spruce, and grassland in western Colorado indicate aspen withdrew 5 inches more moisture than spruce and 9 inches more than grass through a soil depth of 8 feet. There was little difference in the amount of water used from the upper 4 feet of soil on these plots.

Thus it appears that where soils are deeper than 4 feet, substitution of other species would increase yields of water from aspen areas. According to the Wagon Wheel Gap watershed experiment in southern Colorado, (2), the gain would appear during the spring flood period. All trees on this experimental watershed were cut and the flow was increased an average of 0.96 inch (15 percent) for the 7 years after cutting. After the forest was cut, the time of peak flow was advanced 3 days and the rate of flow at the peak was increased by about 60 percent. Eighty-four percent of the increased flow left the watershed before July 10.

Impacts of a program to improve water yield

The treatments now known to increase water yield from the snow zone forest are generally compatible with the best silvicultural and timber management objectives. Most of the coniferous forests are old growth and of an age class suitable for treatment to improve water yield. In general, the valuable timber species can be regenerated by clear cutting in narrow strips or small blocks and are most conveniently managed in even-age stands.

Although the high altitude forests yield material for good quality lumber, poles, pulpwood, and Christmas trees, facilities for harvesting, processing and marketing are limited. A number of studies have been made of market development opportunities for the high-altitude forest products, but narrow profit margins apparently have kept manufacturers from investing in such enterprises.

Lack of accessibility dictates that a road system is needed to properly manage the areas, not only for timber, but for other purposes as well. Road needs for the development and management of the national forests have been proposed to Congress by the Department of Agriculture in a report entitled "Program for the National Forests" (10). Increases in water yields from the spruce-fir, lodgepole, and aspen forests will be only in proportion to progress in developing a road system and in proper logging of the area.

Summary

1. Spruce-fir, lodgepole pine, white pine-larch-fir and pure stands of true firs grow in zones of heavy snow accumulation.

2. Considerable losses of water occur as a result of interception of snow, evaporation and transpiration, and there appear to be appreciable opportunities for improving water yields through forest management.

3. Precipitation averages 40 to 50 inches and the average current yield of water is 20 inches from these forest types.

4. Cutting the forest in strips or small patches has been successful in increasing the snowpack and subsequent water yields from experimental areas.

5. Increased water yields of about 4 inches (20 percent) can be expected from vegetation management.

6. Markets for the forest products and access roads to the forest areas will need to be developed.

DOUGLAS-FIR, HEMLOCK, REDWOOD FORESTS

These forests grow in a belt of very high rainfall along the Pacific coast from Canada into northwestern California (fig. 3). Water yield is estimated to average 45 inches per year, most of the streamflow occurring during the winter months. Most of the streams drain directly into the ocean and little of the water is utilized because of the limited opportunity for storage or diversion of the winter floods. For the present, water yield is less of a problem than is flood protection and preservation of water quality. No research has been done on water yield to date although there may be needs in certain localities in the future. Opportunities for improving water yields appear to be abundant.

INTERIOR PONDEROSA PINE AND DOUGLAS-FIR

Ponderosa pine is found on the south and west slopes between elevations of 3,000 to 5,500 feet in the Northwest and 5,500 to 8,500 feet in the Southwest growing just above the chaparral or piñon-juniper types (fig. 4). At the lower elevations the forest is almost pure ponderosa pine but toward its upper limit the pine mixes with Douglas-fir and aspen, less often with white fir, western larch, limber pine, and blue spruce. Douglas-fir predominates on the cool, moist north and east slopes and on south slopes at the upper edge of the ponderosa pine zone.

Precipitation averages between 18 and 22 inches annually. Winter precipitation is most important for streamflow and for sustaining tree growth, coming largely as snow or mixed rain and snow.

The ponderosa pine type is heavily used for recreation. Picturesque forest trees, streams, lakes, reservoirs, geologic formations, comfortable summer climate, accessibility and abundant wildlife make the pine areas especially inviting.

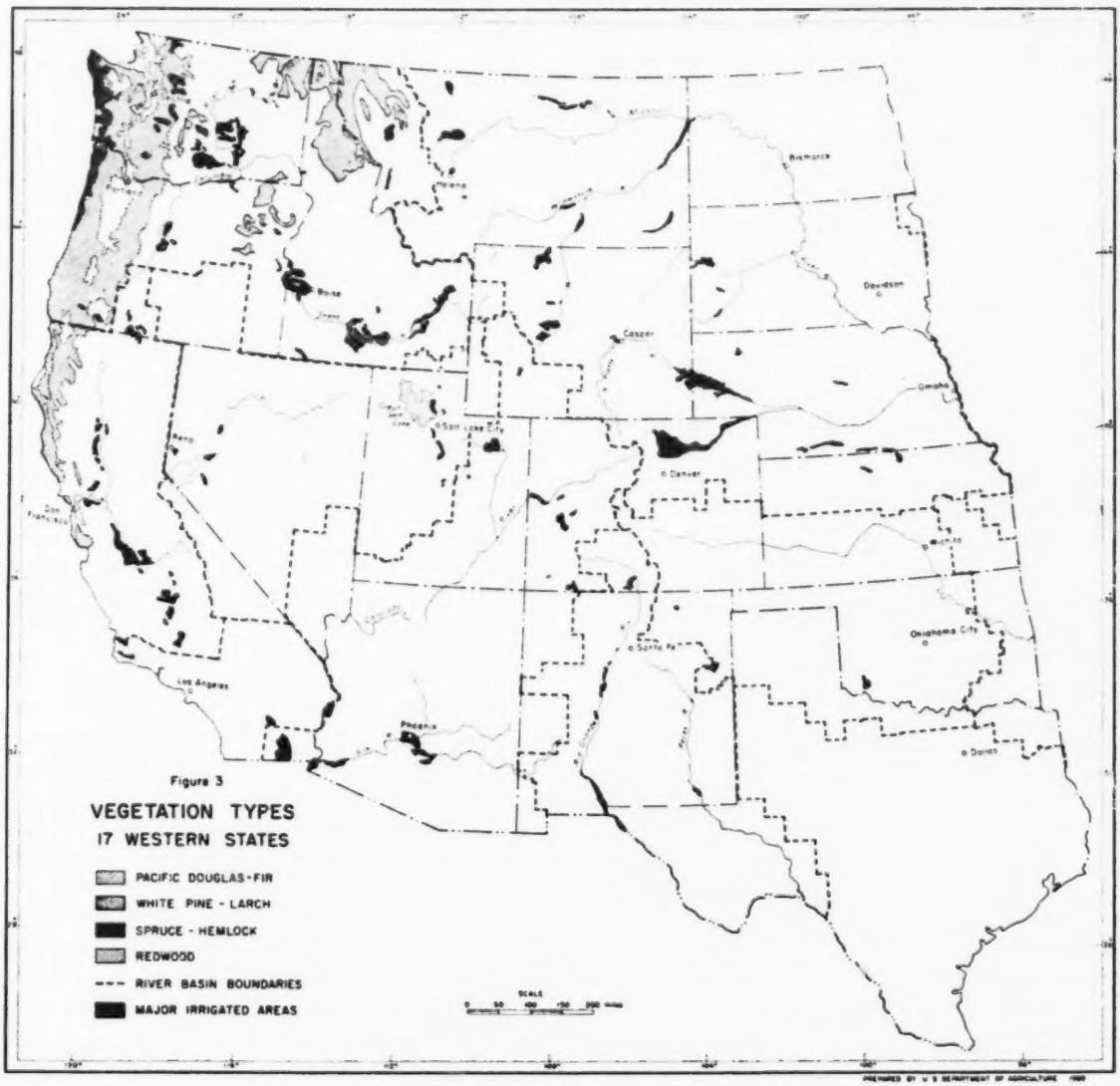
The zone supports some agriculture and a large amount of summer grazing. The open nature of the pine stands permits an understory of grasses, forbs, and shrubs that provides much forage for both livestock and game.

Total area of the interior ponderosa pine is 34.2 million acres and of the interior Douglas-fir, 9 million acres.

Normal water yield

Yield from ponderosa pine areas ranges from 0.5 to 15 inches. The average is estimated to be 4 inches. Interior Douglas-fir water yields are between 1 and 20 inches with an average of 7 inches per year. Streamflow reaches its maximum in late winter or early spring, then declines rapidly during the spring until many streams are completely dry by early summer.

Water quality is generally good unless disturbance has caused streams to become muddy. On steep lands and especially in areas where soils are derived from granites, natural erosion rates are fairly high. Hard thunderstorms frequently occur in summer and these granite areas produce large quantities of sediment and become seriously gullied if care is not used in logging, grazing, and road-building.



Possibilities for improving water yield

Because of high-quality timber and accessibility, interior ponderosa pine has been extensively cut. Clear cutting was common in the early days, but in more recent years cutting practices have tended to remove only one-third to one-half of the merchantable volume by individual tree or group selection. Present-day management reduces canopy density so as to concentrate growth on better trees and safeguards water quality by erosion control. This results in some water yield improvement by reducing interception as well as insuring production of usable water.

Main consideration in the management of this type for water yields must be given to second-growth stands. Many of the second-growth stands of ponderosa pine existing today are overstocked and poor in production of either timber or water. It is believed that measures which will reduce interception will have a significant effect on water yield as well as improve tree growth. This will be particularly effective where winter

snowpack is heavy, or precipitation concentrated in winter, and on cool, shaded slopes protected from wind.

Measures to reduce evapo-transpiration will be effective on deeper soils, especially those deeper than 3 to 4 feet. The high potential evaporation will dry out shallow soils regardless of cover.

Opportunity to change timing of runoff is slight. The snowpack is generally light and melt cannot be prolonged appreciably after the main peak of runoff. Increased water yield will be produced during the flood period and will require reservoir storage to be of greatest utility.

Some ways water yield might be increased are:

(*a*) Reduce density of tree canopy.

(1) Thinning and mistletoe control in sapling and pole-size stands.

(2) Timber harvest in sawtimber stands.

(*b*) Change arrangement of tree canopy.

(1) Create openings in sawtimber canopy by group selection.

(2) Open pole stands by patch or strip pulpwood cuts.

(3) Convert from stands with trees of different ages and sizes to uniform blocks of even ages and sizes.

(*c*) Convert to another plant cover type.

(1) Other trees.

(2) Shrubs.

(3) Grasses.

Most drastic cover change and the one expected to give greatest increased total yield per unit area is conversion from trees to grass. This will be most effective on deep soils where rainfall is abundant. Continuing demands for timber, recreation, and wildlife preclude the desirability of converting large areas of forest lands to grass, but the less productive forests might be so converted.

Based on present knowledge, it is felt that the approved forestry practices now being successfully followed in the management of ponderosa pine will give the most suitable combination of timber and water yields. With more knowledge of hydrologic processes in the zone, prescriptions for the most effective arrangement of trees by sites can be expected. This should increase considerably the efficiency of management for water yield even in areas where timber production is a major objective.

It is difficult to forecast the possible increase in water yield over the interior pine and Douglas-fir type. Some tests have been started and more are needed, but a potential increase in flow between 5 and 20 percent seems possible depending upon local conditions and the kind of forest management applied.

Measures that change density or canopy have largest effects initially. Then there is a gradual decrease until more cutting is done. Full effects will be most felt locally and not over the entire type at any one time.

All measures are least effective in dry years. Average effects are the result of both wet and dry years.

Thinning of sapling and pole-size stands.—Thinning of saplings and pole-size stands is a recommended management practice where the density is too great to permit reasonable growth. Thinning of dense thickets is desirable from a fire-control standpoint, provided adequate disposal is made of trees that have been cut. Thinning of stands normally is favorable to recreational use because thinned stands make a better appearance and permit easier access. Thinning would benefit wildlife habitat by permitting more grasses and browse to grow. The practice is recommended for improved water yields.

Timber harvest in sawtimber stands.—Timber harvesting in the pine type by some form of selection cutting benefits wildlife habitat and range resources, as well as improving forest growth and water yield. Light cutting is beneficial to recreation. It provides for the removal of hazard and insect-risk trees, thus making the area more safe for public use. Salvage cutting may be desirable along scenic highways and along fishing streams.

Converting ponderosa pine to grass.—Complete conversion of anything but marginal stands of ponderosa pine and Douglas-fir to improve water yields is not recommended except perhaps in local and critical situations. Greatest impact would be loss of production of these valuable forest species. Complete conversion would undoubtedly benefit forage production and rangeland conditions for livestock, but it is doubtful that wildlife habitat would be benefited unless clear cutting and conversion were done in not too large patches or strips. Furthermore, the suitability of a converted forest area for recreation would be greatly reduced or even lost by the destruction of camping, picnicking, hiking, or hunting areas. Fire control would be benefited because grass types are generally not

as inflammable or their fires so difficult to control as forest types, especially if they are grazed. However, conversion of these forest types to grass would be done only on selected sites where water yield values clearly outweigh timber and other values of the forest. Water yield may already be enhanced considerably under the present cutting systems.

Summary

1. Interior ponderosa pine and Douglas-fir are important forest types for timber production, recreation, and grazing by livestock and game as well as yield of water. They occupy 43 million acres.

2. Precipitation averages between 18 and 22 inches, of which an estimated 4 inches (20 percent) is yielded to streamflow.

3. Much of these forest types have been cut over and the opportunities for improving water yields will be found in thinning and selectively cutting in second-growth stands.

4. Experience is limited but it is estimated that careful management of ponderosa pine and Douglas-fir forest can result in 0.5- to 1-inch increase in water yield over that being produced on unmanaged lands.

CHAPARRAL AND WOODLAND OF CALIFORNIA AND ARIZONA

The transition between forest and grasslands in the mountain areas of the West is a zone of shrubs or stunted trees called chaparral or woodland grass (fig. 5). Elevations range from 100 to 5,500 feet.

In southern California chaparral sometimes with minor conifers covers about 7.5 million acres. Coastal sagebrush and associated brush types occupy about 3.5 million acres. Woodland-brush and woodland-grass types are found on about 9 million acres in and around the edges of the Great Central Valley. In Arizona, chaparral covers about 5.5 million acres at elevations from 4,000 to 5,500 feet on the southern edge of the ponderosa pine type.

Moderate temperatures, winter rain, and dry summers characterize the climate of the chaparral and brushland areas. Annual precipitation ranges from 12 to 40 inches but averages only about 20 inches (table 1) and 60 to 75 percent of the year's precipitation occurs in a few storms during the period November through March—the larger storms often being very intense intermittent rains. Extreme rates have been recorded, such as 1.02 inches in 1 minute and 20.20 inches in 24 hours. Less than 20 percent of the precipitation is snow.

Chaparral and woodland species are deep rooted, drought enduring and during dry periods are highly inflammable. Many species sprout profusely. In a few weeks after chopping or burning vigorous sprouts arise from the crown and in 3 to 5 years the stand is again rather dense. Also, seeds of many of the species germinate best after having been heated, so that dense stands of seedlings often develop after fire. In central California there is much interest in the use of fire to convert brushlands to grass.

Chaparral areas, particularly in southern California, are important sources of water but are subject to severe floods and erosion once the protective cover is destroyed. Because of the dense population and the multimillion-dollar investment in reservoirs, debris dams and basins, settling basins, and water distribution systems in and immediately below the chaparral zone, the most important function of chaparral is watershed protection.

Normal water yield

Water yields from the chaparral and woodland areas are erratic. Total annual yields average about 5 inches in southern California chaparral, 1½ inches in Arizona, and 7 inches for the woodland areas of central California. In years when precipitation is low there may be almost no runoff, whereas in certain favorable areas during years of high rainfall there may be as much as 25 inches of runoff, mostly during the winter months.

The concentration of rainfall in winter requires storage for summer use. Water for storage must be reasonably clean to prevent loss of storage capacity to useless sediment, even where runoff is to be used to recharge underground water storage basins. Thus, it is highly desirable to prolong the runoff period and to reduce sediment loads.

Possibilities for improving water yield

Because of the strategic location of chaparral and woodland areas in relation to centers of population and important irrigation farming, the development and application of methods for increasing water yields from these areas are being studied,

particularly for converting the chaparral to a different kind of plant cover.

Conversion to grass.—Trials on watersheds are too new to permit judging the full effects of conversion on water yield, but in California results indicate that on deep soils yield may be increased as much as 2 inches on areas converted from brush to grass. This amount will vary greatly with seasonal rainfall. Once grass is well established, surface runoff and erosion will be stabilized and increased yield will be largely from seepage.

On the basis of available information, an average increase in water yield of 1 inch could be expected in California and perhaps one-half inch in Arizona, from conversion of chaparral to grass.

Surveys indicate that 3.3 million acres (30 percent) of chaparral and 6 million acres (69 percent) of woodland in California have a good to fair potential for grass establishment and maintenance. Standards used prescribe that soils be more than 18 inches deep and that infertile soils on south and west slopes be left undisturbed. Only a small

Figure 5

VEGETATION TYPES
17 WESTERN STATES

proportion of this can be classed as highly productive for forage growth. Reconnaissance estimates in Arizona indicate that thin soils and steep slopes will limit the possible area for conversion to less than 1½ million acres, or 25 percent of the total area.

Burning of the brush cover is often advocated for conversion to grass but unless seeding is done and sprout growth is controlled, this often results in serious erosion and only slight benefit to forage production. Also, great care is required to prevent fire spreading to adjacent lands. In northern California, costs have ranged from $1 per acre for burning, with no followup work, to $25 or more for mechanical burning, spraying, and seeding measures. In southern California and most of Arizona, costs would be higher because of the precautions necessary to prevent fire escaping and to prevent erosion from the steeper lands.

Conversion to grass would probably benefit control of wildfires by providing control lines and safety zones for firefighters.

Research in California (6) and Arizona (7) shows that grasses have more shallow root systems and shorter growing seasons than the native brush species. However, in the long, dry seasons even grass will use all the available soil moisture where the soil is less than 3 feet deep. Converting to grass will not save water on deep soils if rainfall is insufficient to replace soil moisture used by evapo-transpiration in the preceding season. This means that greatest increases in flow are possible in wet years and least or perhaps no increases during dry years.

The conversion of brush to grass carries considerable risk of erosion. Areas to be treated should be carefully selected and steep slopes and shallow or infertile soils should be excluded (3) (4). Experience on selected areas indicates that erosion may be extremely high during conversion, but once grass is established and is maintained, erosion may be less than under brush cover.

Summary

1. The chaparral and woodlands of California and Arizona occupy 25 million acres and often form important watersheds above irrigated areas and municipalities.

2. Climate is moderate and precipitation averages about 20 inches, much of it from intense, intermittent winter storms.

3. Annual water yields are highly variable but average about 5 inches in southern California, 7 inches in central California, and 1½ inches in Arizona.

4. Preliminary indications are that conversion of brush to grass may result in average increases 1 inch of water in California and 0.5 inch in Arizona. Only about 30 percent of the chaparral and 69 percent of the woodlands are suited to this treatment.

5. Burning has been used for destroying chaparral cover but many precautions and much followup is required to prevent escape of the fire, to prevent erosion, and to establish and maintain a new cover of grass. Herbicides can be used to suppress sprouting of some brush species.

PIÑON–JUNIPER

The piñon pine-juniper type occupies a large part of the transition zone between forest and open lands, especially in the watersheds of the Colorado and Rio Grande Rivers and in the Great Basin. It forms a woodland belt just below the ponderosa pine zone. Piñon-juniper and sagebrush alternate over thousands of square miles, the former occupying rough broken areas or shallow stony soil, while sagebrush occurs in the more level and deeper soils.

The type covers 61.4 million acres, 51 million acres in the States of Utah, Colorado, Arizona, and New Mexico (fig. 5).

Annual rainfall is 10 to 20 inches, coming mostly in summer in Arizona and New Mexico but changing to winter precipitation further north (table 1). Long rainless periods are common and evaporation rates are high. High winds during dry seasons cause considerable soil movement.

There is a wide range of soil types but, typically, soils are shallow and extremely rocky.

The most important use of land in this type is for livestock and wildlife range. Only small areas have proven practical for either dry farming or irrigation. Wood from the piñon pine and juniper trees is important locally for mine props, fenceposts, and fuel. Piñon nuts are used for food and as a cash crop by local Indians.

Heavy grazing use has favored the spread of juniper into areas once dominated by grass, and in some places, particularly in Arizona, cattlemen and range-management agencies have undertaken

juniper eradication to increase grass production. Studies have recently begun on the effects of this practice on water yields.

Normal water yield

There are no watersheds entirely within the piñon-juniper type that have perennial flow. Average water yield is low, occurring mostly as overland flow during thunderstorms. Rarely, and in limited low-lying areas, are soil moisture deficiencies satisfied. Maximum water yield comes from areas with extremely shallow soil depths such as those found on sandstones.

Average annual water yields may vary from 0 to 3 inches, but the estimated average is only 0.5 inch. Most runoff results from intense summer storms, usually of short duration. The flashy runoff causes high flood peaks, frequent property damage, and carries large volumes of sediment. Soils are easily eroded and plant cover is seldom dense enough to give adequate protection. The type is not considered an important source of water for downstream areas.

Possibilities for improving water yield

Investigations of the possibilities of improving water yields in the piñon-juniper type are beginning, but the prospects are not encouraging. Generally, soil moisture deficiencies far exceed changes that could be caused by management of vegetation, but there are a few places where precipitation exceeds 18 inches that some increased yield might be achieved. Here conversion from trees to grasses with more shallow roots may give increased water yield, at least during wet years. Perhaps 5 to 10 percent of the total area of the type is suited for management of this kind. An optimistic estimate would grant an increase of 0.25 inch on the area treated.

Sediment control is a major problem on the type and should be accounted for in a program of conversion to grass. Because chances for improving water yields appear to be slight, probably the most efficient use of the precipitation is to increase forage production and improve grazing management throughout the type. Because of the large acreage and the low value of the present cover a program of research is justified.

Costs of juniper control range from $1.50 per acre to $10 per acre depending upon the density of the stand and the degree of control desired. These include costs of cabling, followup by dozer or by hand, and reseeding to desirable grasses. These costs do not include disposition of the uprooted trees. The Bureau of Indian Affairs reports an average cost of $6.49 per acre, using various methods on 134,000 acres.

Assuming that 10 percent of the piñon-juniper can successfully be converted to grass, about 6 million acres might be included.

Summary

1. The piñon-juniper type forms a transition belt between the open grass and shrub lands and the forest. The piñon pine and juniper are intermixed with grass and shrubs.
2. The type is characterized by low precipitation and high evapo-transpiration, the combination of which results in serious moisture deficiencies.
3. Present water yields average only 0.5 inch per year, this amounting to only 3.3 percent of the total annual precipitation.
4. Prospects for improving water yield are not great—perhaps 0.25 inch on 10 percent of the piñon-juniper lands.
5. Improvement of piñon-juniper lands for grazing appears to be the most efficient use to be made of the precipitation falling on them.

SEMIARID GRASS AND SHRUB

The semiarid grass and shrub type includes the short grass of the Great Plains, sagebrush-grass, semidesert shrub and grass, mesquite, and related plant associations. This broad combination of types occupies about 330 million acres and extends from Canada to southwest Texas and from eastern California to the farmlands of Nebraska, Kansas, and other Midwestern States (fig. 6). Within this broad zone are islands of other vegetative types, but the zone is generally characterized by low precipitation and sparse, low-growing vegetative cover.

Annual precipitation varies from 5 to 20 inches, averaging about 12 inches, with winter precipitation predominating in the North and summer precipitation in the South (table 1). Temperatures are extreme, ranging from minus 40° F. (approximate) to 120° F. Evapo-transpiration potentials likewise show wide variation, from about 25 inches in the north to 75 inches or more in south-central Arizona. Average evapo-transpiration potential, considering the area as a whole, is about 27 inches.

Normal water yield

Average annual water yields from the zone are estimated to vary from 0.1 inch to about 1.0 inch with an average of 0.4 inch. This 0.4 inch of runoff is only 3.5 percent of the average annual precipitation; the remainder is evaporated or used by vegetation. The evaporation potential is more than twice the average annual precipitation. Also, runoff normally occurs only from high intensity rains falling at rates which exceed the infiltration capacity of the soil. Most storms are more gentle and the rain is absorbed by the soil mantle to be subsequently removed by evapo-transpiration.

Much of the runoff from the uplands of this semiarid area is absorbed in the dry and usually deep and porous alluvial stream channels, and this undoubtedly accounts in part for the low water yields. The processes and extent of these transmission losses are poorly understood and deserve considerable study.

In spite of low water yields, floods containing comparatively small volumes of water often cause excessive erosion. This sediment production is

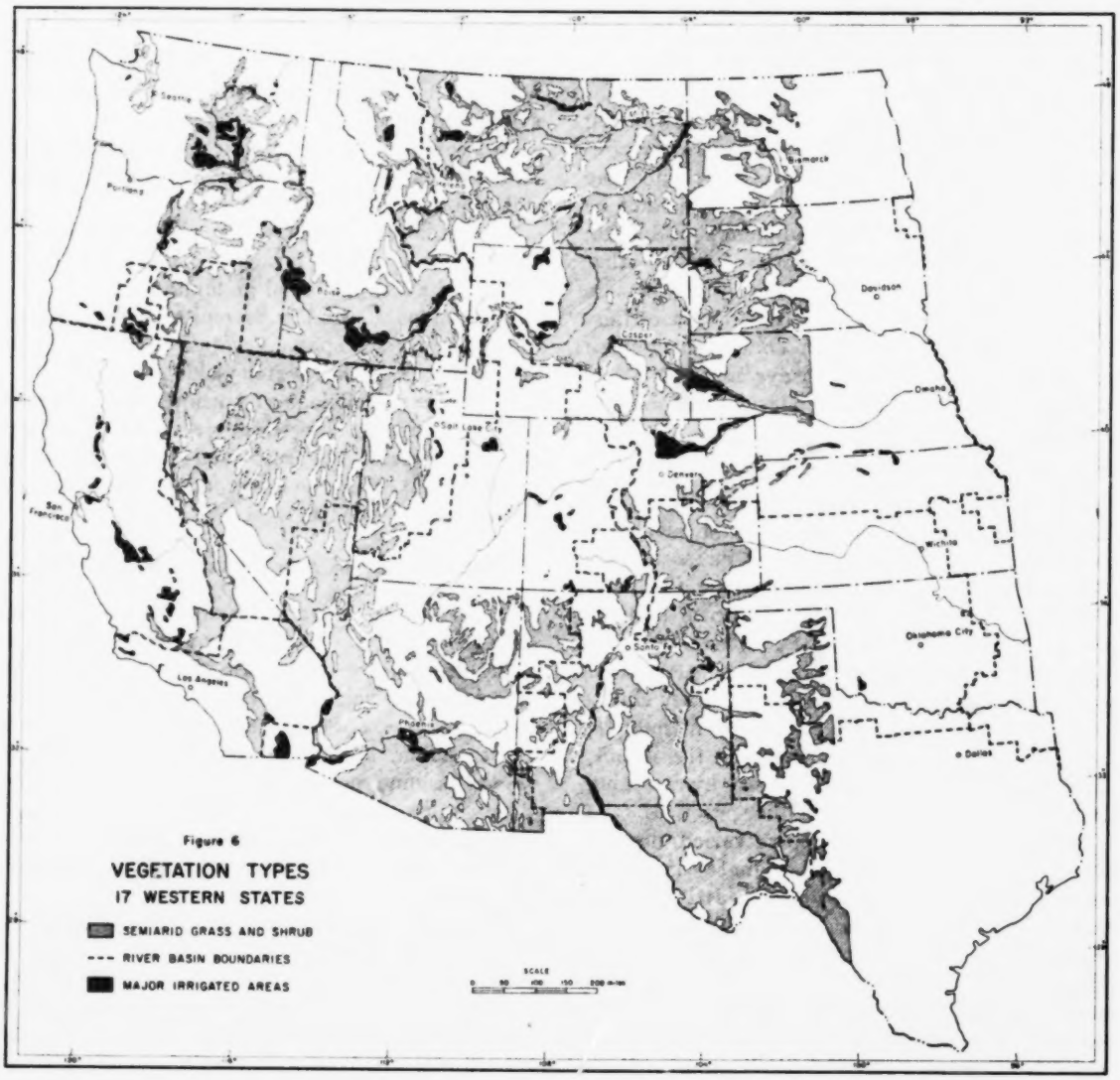


Figure 6

VEGETATION TYPES
17 WESTERN STATES

serious, resulting in the filling of irrigation and other reservoirs and major stream channels. Estimated sediment production from this semiarid zone ranges from 0.1 to 3 acre-feet per square mile per year.

Possibilities for improving water yield

Little study has been made of the hydrology of the semiarid grass and shrub lands, and the potential for water yield improvement through vegetation management is not clear. Present knowledge of hydrologic processes, as developed under conditions of higher rainfall, suggest that treatments which would cause rapid surface runoff from these lands would likely increase water yields. However, since vegetation cover on these semiarid lands is sparse at best, and considering the small amounts of water now being derived from these semiarid lands, severe management practices which would further reduce the cover and cause compaction of the soil cannot be advocated. Erosion and sediment production would become even more serious. On the other hand, removal of certain kinds of vegetation such as shrubs or other deep-rooted species may increase water yields. With continued research in watershed management, ways may be found to increase water yields in semiarid areas without accompanying serious erosion.

Other possibilities of vegetation management

In view of the characteristic low precipitation of the semiarid grass and shrub zone, emphasis should be given to the opportunities for increasing the efficiency of use of rain and snow on the lands where it falls, through control of brush and improved management practices. These improvements might include: (*a*) Control of such brush species as sagebrush, mesquite, and other shrubs having little or no forage value; (*b*) introducing desirable grasses; and (*c*) increasing the density of existing stands of palatable grasses by reseeding, improved management, and similar practices.

Results of these practices have varied, depending on the favorableness of climate, soils and other factors, but it has been clearly demonstrated that under favorable conditions existing grasslands can be improved, even with no additional water. Not only is forage production increased but sediment production rates are often reduced, sometimes as much as 55 percent. Obviously, such reductions in sedimentation rates can have a material influence on the siltation of storage reservoirs.

It is estimated that forage production can be improved on 90 percent of the 330 million acres of the semiarid grass and shrub zone, and that the present forage production can be increased 2.7 times if the ultimate potential is realized. An increase of even 100 percent in forage production over an area of almost 330 million acres would represent a major change in the present usefulness of available water supplies in the Western United States and would significantly reduce erosion.

Summary

1. The semiarid grass and shrub zone is characterized by low precipitation and high potential evapo-transpiration.

2. Vegetation cover, made up of mixed grass and shrubs, is generally sparse leaving much soil exposed to potential erosion.

3. Present estimated water yields average 0.4 inch which accounts for only 3.5 percent of the estimated average annual precipitation.

4. Because of the low precipitation, small runoff and naturally sparse vegetation cover, opportunities for increased water yields are small.

5. Increased efficiency by using water where it falls for increased production of range forage through control of brush and improved range management offers the best course of action based on present knowledge.

PHREATOPHYTES AND RIPARIAN VEGETATION

After streams leave the humid mountains, the only green vegetation during most of the year is along the watercourses. In the forest and for some distance below, the most typical species are alders, maples, mountain ash, aspen, and willows. Lower down, sycamores are found and cottonwoods become prominent following the streams through the plains. Streams that flow through semidesert regions have channels lined with seepwillow, arrowweed, mesquite, and tamarisk (saltcedar).

The word phreatophyte (well plant) describes those plants whose roots extend into the underground water table or the capillary fringe above it. The U.S. Geological Survey estimates that phreatophytes cover about 16 million acres in the

Western States and use 25 million acre-feet of water annually (8). They are considered to be wasters of water.

In their lower reaches, most western streams pass through flood plains where gradients are slight and they drop much of their sediment loads The expanse of wet sand and silt favors establishment of phreatophytes. But these conditions also favor high evaporation losses even without vegetation. Sediment accumulations cause water to spread out in flat shallow sheets, or channels are dammed to form warm shallow lagoons, increasing the surface exposed to evaporation. The growth of plants on sandbars often forms barriers to flow and increases the amount of sediment deposited. More sites are then available for plant growth and a vicious circle operates to spread the river and the phreatophytes over a wider area. An increase in phreatophytes is often a symptom of poor water management, not always a cause.

In upstream areas, riparian vegetation is not always detrimental to water supply and often serves a useful purpose The transition takes place somewhere in the chaparral zone where othee values become important. There is little doubt that wet-site vegetation uses considerably morr water than the shrubs on the dry slopes, but there is also a concern about protection from erosion, the preservation of habitat for fish and game, and the beauty of the site. Even in the brush zone, other values must be considered where water values require changes in riparian vegetation.

Higher, in the true forest areas, climate is more humid and riparian vegetation is surrounded by other kinds of trees which provide shelter from hot dry air. There is no evidence to show that streamside trees use appreciably more water than those elsewhere in the forest unless soil moisture becomes depleted. Yet, it is certain that they are exceedingly important to recreation, to provide a desirable environment for fish and wildlife, and to prevent streambank erosion. Conclusions on the advantages of phreatophyte control in arid areas should not be applied to forest vegetation along streams without careful measurement and study.

Possibilities for improving water yield

Phreatophyte vegetation uses water during summer when it is most needed for useful purposes. Because rate of use decreases with increasing depth to ground water, areas of shallow water table should receive first consideration.

The basic ways of reducing waste of water by phreatophytes are—

(*a*) substitute useful plants for those of little utility.

(*b*) control phreatophytes by mowing or chemical spraying to reduce foilage area.

(*c*) through management, favor species which use the least water.

(*d*) divert water away from phreatophytes by piping surface flow or by pumping to lower the water table beyond the reach of plant roots.

Control of phreatophytes should be supplemented by the establishment of more desirable vegetation. Simply destroying phreatophytes, without thought of replacement, will only temporarily increase water yields. Streamside sites are favorable for vegetation and some kind of plants will quickly become established.

Preventing the spread of phreatophytes into new areas will require more knowledge of the ecology of the individual species. Recent studies of tamarisk have revealed situations to which this plant is adapted and also have shown how controlled changes in water level can be used to control invasion.

In some areas on the Rio Grande above Elephant Butte Dam, phreatophytes have been cleared away to raise crop plants. Root plowing methods promise to improve efficiency of such clearing. Along levees, tamarisk foilage density is reduced by repeated mowing and chemical spraying. New chemicals have aided this work. Channelization of the Rio Grande by dredging has prevented water from spreading out and has reduced recharge of phreatophyte areas.

Bermuda grass is an effective competitor of tamarisk on the Salt and Verde Rivers in Arizona. The grass is assisted by grazing because cattle also browse the tamarisk, controlling its spread. The low-growing grazed grass requires less water than the tamarisk and provides more valuable forage.

Opportunities for salvaging water now used by phreatophytes will increase as more knowledge is obtained. Just how much can be saved is not known, but Robinson (9) estimates that in Nevada 25 percent of the water now used by phreatophytes could be salvaged. This amounts to 400,000 acre-

feet. In Arizona, he estimates the possible savings to be about 50 percent or 700,000 acre-feet. If water now used by phreatophytes could be reduced by 25 percent in the 17 Western States, the possible saving would be over 6 million acre-feet or 1.4 percent of the present total yield.

Summary

1. Phreatophytes are thought of as being wasters of water, using an estimated 25 million acre-feet annually.

2. The phreatophyte problem is particularly important in the drier parts of the West.

3. Phreatophytes can be controlled and water supplies increased by—

(*a*) Mowing and spraying with herbicides.

(*b*) Plowing with root plow.

(*c*) Replacement with more useful vegetation.

(*d*) Diverting water away from phreatophytes by piping or pumping.

4. A 25-percent saving in water now used by phreatophytes appears possible. This is equal to 6 million acre-feet or 1.4 percent of the total annual water yield from the 17 Western States.

ALPINE ZONE

The alpine zone includes the area above the limits of tree growth. Frequently there is a transition belt of wind-trimmed prostrate trees extending down to the true forest, but the plant cover is mostly ground vegetation or dwarf willows.

Alpine climate is cold and windy. Snowfall is moved about by fierce winds before it finally blows off the ridge or comes to rest in a sheltered spot. Continuous snow cover is rare even in winter. The alpine seldom has as much as 2 feet of snow except in protected spots where drifts of 20 to 40 feet in depth are common. These drifts are important in maintaining summer streamflow because they furnish melt water long after the rest of the mountain snow has disappeared. These snowdrifts lose little water to evaporation. In fact, during certain temperature and humidity conditions condensation adds water to the snow. Alpine snowfields are efficient water reservoirs.

It is estimated the alpine zone covers as much as 10 million acres in the Western States. Present land use, if any, is grazing by livestock and game but it is an increasingly important area for hiking, pack trips, winter sports and other recreation. Watershed values are great. Water yield from this zone is estimated to average 32 inches. A portion is included in wilderness areas and national parks.

Possibilities for improving water yield

It appears technically feasible to increase accumulation of deep snowdrifts and thereby increase the storage of water in the mountains. In Colorado, an addition of 2 feet of depth to an alpine drift will give one more week of snowmelt and produce a little more than an acre-foot of water per acre of drift.

An effective way is to place an additional wind barrier just upwind from existing drifts or from places where drifts almost accumulate. Snowfences of various types or trees might be used. Another method of accumulating deeper snow is to break off cornices and avalanches where they will do no harm. The objective is to keep these natural snow traps operating at high efficiency by preventing them from filling completely and by moving the snow to a protected accumulation area downslope and to increase their capacities. A further possibility is the use of coatings or chemicals to delay or increase melt to suit water demand.

These methods are not expected to increase total water yield but promise to make available more usable water at a suitable time.

Increased snowdrift accumulation may also increase the hazards of avalanches. This subject deserves a great deal more research.

APPLICATION REQUIREMENTS AND LIMITATIONS

In this discussion of vegetation management and water yields, broad categories of vegetation have been considered. It has been pointed out that each of these categories is highly variable as to climate, soils, and relative capacity to yield water. The report has dealt with broad averages but these averages may not be representative of a given local situation or watershed. No consideration has been given to whether lands are in public or private ownership, and only brief mention has been made of the condition and past use of the different categories of vegetation. Lands not subject to cover manipulation because of institutional restrictions are generally not considered in this report. The report has called attention to some of the conflicts to be encountered in the management of vegetation for improved water yields. The ap-

plication of treatments is complicated and deserves further consideration.

Table 1 shows potential initial increase in water yield for the different vegetation types. It also shows area within each of the types and percent of area of each type that physically could be treated in some way to improve water yield. The reader of this report should be cautious about multiplying these figures to obtain an estimate of acre-feet of water. In large part the increases in dicated in water yield effected by vegetation management will be local rather than basinwide and do not necessarily represent increases at point of withdrawal for use. Treatments can be applied to only part of the acreage of any given vegetation type at any given time. Furthermore, unless a complete and permanent conversion is made from one type of vegetation to another, the effects of vegetation management will probably give a maximum increase immediately following treatment, but gradually decrease over the years as natural recovery of vegetation occurs. It is not known how long these treatment effects will last.

To illustrate how water yield increases resulting from vegetation management might be spread over the acreage of a vegetation type, the lodgepole pine and Engelmann spruce-fir types are considered as a hypothetical example. Together these types occupy about 22 million acres, 70 percent or 15.4 million acres of which is considered treatable for improved water yields. In the management of lodgepole pine and Engelmann spruce-fir stands a 125-year rotation is often practiced. For a given acre this means that under sustained yield management a new stand of timber is grown and harvested every 125 years. It has been shown earlier in the report that cutting this timber in small blocks or strips results in estimated initial annual increases of 3 inches of water. It is assumed that annual increases in water yield will gradually reduce until zero is reached after 25 years, resulting in an average annual increase due to cutting of 1.5 inches over the 25 years. To determine the annual increase in acre-feet of water from 15.4 million acres of treatable area, the acres in these forest types, 15,400,000, are multiplied by the average inches increase divided by 12 (1 foot) to give 1,925,000 acre-feet. But the increase lasts only 25 years so in a 125-year rotation only $\frac{25}{125}$ or one-fifth of the acreage is producing increases at any given time in the rotation. Therefore, $1{,}925{,}000 \times \frac{25}{125} = 385{,}000$ acre-feet increase in water each year from this entire type area.

The above illustration is based on management of these forest types primarily for timber production with increases in water yields only incidental. The more frequently an area is cut the more continuous will be the increases in water yield. If the lodgepole pine and Engelmann spruce-fir forests were to be managed primarily for water, the optimum rotation might be cutting every 25 years so as to obtain a continuing increase in yields of 1.5 inches per year. This would produce a total annual average increase from these forests of $15{,}400{,}000 \times \frac{1.5}{12} = 1{,}925{,}000$ acre-feet, or 5 times as much increase in water as obtained under management primarily for timber production. This type of management would not produce commercial yields of wood products.

Cutting on a 25-year rotation is generally not practical because the timber stand could not be satisfactorily reproduced in that short time. In order to manage this forest type for both sawtimber and water, a rotation of approximately 125 years must be followed. However, if the aim of managing these lands were to produce pulpwood, a rotation of 50 years might be followed. This would give annual average water yield increases of 962,500 acre-feet and trees which would average about 7.5 inches diameter breast high at this rotation age. Market demands for pulpwood would need to change considerably to make this size material commercial.

The example of the lodgepole pine and Engelmann spruce-fir forest types is one of the more simple for illustrating the effects of treatment on water yield because in these types clear-cutting by blocks is an accepted forestry practice. In forest types where high-level silviculture requires intermediate cuts during the rotation, before the final harvest cut is made, the complexities of computing acre-feet of water yield increases are multiplied.

The economics of managing forest lands in private ownership for water yields may be even more difficult than for public lands because of the need to consider maximum dollar returns. Public

land management, on the other hand, considers other public values as well.

In order to accomplish improved water yields on private lands, a program of extension and education may be necessary, both as to methods of management and concepts of using lands for several purposes. Managers of public lands also will need more training in methods of management for water and in judging those situations where water production opportunities are best and where high priority should be given to water as a land use.

The Department of Agriculture administers many millions of acres of national forests and other public lands that are important sources of water. In the administration of these lands under the principles of multiple use and sustained yield, consideration is given not only to water but also to the other renewable resources of timber, forage, wildlife, and recreation. Manipulation of vegetation to increase water yields cannot be the sole objective of management.

In the administration of these public lands there are two principal parts of watershed management:

(1) Protection of the watershed by stabilizing the soil and thereby preserving and improving water quality.

(2) Management of the area to improve water yields.

Protection of the watershed and water quality will continue to be a primary objective. Water yields receive major consideration in the multiple-use management of national forests. Modification of management practices to improve water yields will be undertaken when proved practicable by research and trial application and when overall public benefits will be enhanced. Although the general policy will be to favor water in applying the multiple-use principle in areas of water scarcity, this does not mean that in every such locality water will be given first priority or that land management always will be oriented toward maximum development of the water resource. For example, in some places recreational values will be dominant, as at camping and picnicking spots or in wilderness and wild areas. In other localities the preservation of natural streamside vegetation for benefits to fish and wildlife would be of first importance. In all instances the relative importance of other resources will be carefully weighed against the public benefits to be gained by modifying land-use practices to enhance water yield. The overall objective is to manage the national-forest lands so as to obtain the optimum combination of uses which will benefit the public as a whole.

Many forest and range lands of the West are in a deteriorated condition from past mismanagement and are producing turbid sediment-laden water. In such areas the first objective must be rehabilitation and protection rather than increasing water yield, because even small deteriorated areas can greatly reduce quality and usability of water in larger streams. These conditions apply to some of both private and public lands. The importance of this condition is illustrated in the Department of Agriculture's program for the national forests (10) which includes proposals for 10,000 miles of gully and channel stabilization, erosion control on 14,000 miles of substandard roads and trails, revegetation of 4 million acres of damaged rangeland and tree planting on more than 3 million acres of understocked forest land.

From the broad point of view the most important function of watershed management is to protect the watershed and to maintain or improve water quality. Locally, good watershed management can do several things beyond this such as improve water yields and reduce flood hazards. Programs for increasing water yields through vegetation management should be wisely and carefully selected and applied.

Pilot programs to test the application of knowledge already in hand can be undertaken at this time, but it is recommended that large-scale action programs be implemented only as rapidly as large gaps in knowledge are filled in and as the local situation warrants.

Presently accepted management practices on some of the vegetation types are those which appear to favor water yields as well as other resource production. Programs can go forward on these areas without change and with expected yields similar to those now being realized.

In the lodgepole pine, Engelmann spruce-fir forests, sustained yield cutting should proceed as rapidly as feasible with the development of improved logging methods, roads and markets for the forest products. This will result in increased water yields in local cutting areas.

In the interior ponderosa pine-Douglas fir usable water yields will be most benefited by improving the stands on cutover lands and thinning the

overdense stands of reproduction now producing little water or forest products. Marginal pine areas might be considered for conversion to grass.

RESEARCH

Research on the management of vegetation to improve water yield is new. Studies now in progress are producing some interesting and worthwhile results but many of these studies are long-time in character and only a few of the many problems and relationships are being explored.

The research program now active in the Department of Agriculture involves studies of hydrologic processes, studies of the efficiency of water use by various forms of vegetation and watershed studies testing land treatments or land-use practices and their effects on water yield and quality. For example, research has shown that because of differences in length of growing season, depth and type of root system, and top growth characteristics and color, transpiration rates are not the same for all vegetation. The amount of water required to produce a unit of dry weight is not constant and some plants make considerably more production on available water than do others. Furthermore, cropping and tillage practices, conversion from one type of vegetation to another or methods of logging or harvest of the vegetation may change the quantity and quality of water yield. The present research program is well formulated but small, and there is not adequate coverage of the many problems involved.

In order to understand the relationships of vegetation to water yields, it is necessary to learn what processes are involved in these relationships, how these processes function and how they can be modified and used in the management of water-yielding lands. In the 17 Western States there are many combinations of vegetation, climates, soils, and land uses, and it appears necessary to build a fund of knowledge of the interactions of these factors with water behavior to be able to predict, with limits at least, the results of several alternative kinds of vegetation management on water yields.

Recommendations for further research

To improve water yields by managing vegetation on watersheds, research must provide information on the processes of (*a*) interception of precipitation by vegetation, (*b*) infiltration and percolation of water into and through the soil, (*c*) transpiration of water by vegetation, and (*d*) evaporation from plant, soil, and plain water surfaces. All research in vegetation management and water yields will involve to some degree the influence of these processes.

Interception.—The importance of interception in the water balance must be established and related to kind of vegetation cover, kind of precipitation, and amount and intensity of storm.

Precipitation that does not reach the ground and is evaporated directly has little effect on water yield. However, energy relations indicate that intercepted moisture has a direct influence on transpiration rates of the vegetation and on evaporation of surface and soil moisture. These relationships need to be established.

Infiltration and percolation.—Infiltration is affected by the nature of the soil, its physical condition, and the amount and kind of litter and humus at the soil surface. Kind and amount of vegetation, use of the land, and intensity and amount of rainfall are some of the factors involved that need to be studied and interrelated. From this should come concepts of establishing different combinations of vegetation cover and soil to increase soil and ground water, on the one hand, or to increase the amount of runoff on the other.

Percolation, being the process of deep penetration of water into the earth's surfaces, is perhaps less manageable but also less understood. Exactly what happens to water that goes to deeper levels; how rapidly does it move; how much reappears at the surface or goes into deep storage; and what are the factors of soils and geology that influence this water movement? All of these questions need further study as they bear on water yields from managed watersheds.

Evaporation.—Before effective and economical techniques for reducing evaporation can be developed, fundamental studies on the basic mechanisms of water loss from soil, plant, and free water surfaces will be required. Particular attention needs to be given to movement and loss of moisture as affected by soil conditions, cultural and management practices. Future research must place more emphasis on the influence of kind, size, and arrangement of vegetal cover and plant residue upon the amount of solar radiation received at the ground surface and its relation to evaporation.

In some marginal areas, it may be desirable to stabilize and seal the soil surface by mechanical or chemical means to prevent surface evaporation. Stock ponds are believed by some to be wasteful of water by evaporation, seepage, and deep percolation. Research is needed under a wide variety of climate, soil, geologic and topographic conditions to devise the most efficient methods of providing stock water of satisfactory quality.

Snow is a major source of western runoff and more needs to be learned of the processes of evaporation, condensation, and melting as they are influenced by vegetation, elevation, aspect, slope, and other factors. Coatings or additives to reduce evaporation and sublimation or control melt need to be developed and evaluated. Better methods of increasing depth of snowdrifts would decrease evaporation losses and prolong melting.

Transpiration.—Research has shown that plants differ in water absorption, transpiration and efficiency of water use. Knowledge on how plant species absorb and transpire water in response to incoming energy, wind, humidity, soil moisture supplies, and soil aeration is essential to greater water use efficiency Regulatory mechanisms within plants that directly or indirectly regulate water absorption and transpiration must be studied in a strengthened research program. The limited amount of past work has been done almost entirely with cultivated plants or tree seedlings in greenhouses or other controlled environments. Research under natural conditions is also important to facilitate the selection and development of plants which have a minimum water requirement in addition to a high yield potential.

Evapo-transpiration—evaporation and transpiration combined—accounts for a large part of the difference between precipitation and runoff. A concentrated and continuing basic research program on soil, plant, water relationships offers many opportunities for reducing evapo-transpiration and thereby improving water yields and water use efficiency.

Management of brush and rangelands

Preliminary investigations have shown that in certain situations, onsite water yields can be increased by converting chaparral and other woody vegetation to grass. Specific cover types, soils, slopes, and climatic conditions under which significant increases in streamflow can be safely obtained by conversion of brush to grass, however have not been determined. Studies to determine water consumption, infiltration, quality, and yield from brush areas as compared with grass areas will give some of this information. Practical methods of converting brush to grass must be based on research in plant physiology and ecology, and should include studies of the control of brush and the establishment of seed grasses in relation to genetic and environmental factors.

There are vast acreages of range and brushlands where vegetation has been destroyed or is exceedingly sparse, and these are sources of floods and sediments. Research will aid the development of sound management practices to purposefully reduce flood hazards, improve the quality of runoff from these lands, and establish the most useful and efficient kind of vegetation.

Management of forest trees and stands

Knowledge of the use of water by different species of trees and the effect of age and arrangement of trees on water use efficiency is scanty. With this knowledge, it is possible that a greater amount of wood could be grown on the same or even less water. A better basis is needed to guide thinning and stand-improvement cuttings, as well as decisions between uneven and even-age management and rotation age. New logging methods must be developed for sites now inaccessible or where present methods would cause excessive erosion. Also important is the development and testing of cutting methods that will increase late season flows.

Management using fertilizers

Present research indicates possibilities of using fertilizer in management for water yield, particularly on crop and range lands. Interrelationships of fertilizer use and grazing management practices as they affect water yield and quality have not been established, and the interrelated effects of fertilizer and grazing management on drought survival of range vegetation are not known. Futhermore, the use of organic compounds and plant residue byproducts as soil amendments may alter soil structure and erodibility sufficiently to affect the quality and quantity of water yield. The use of fertilizer in conjunction with forest-management practices needs to be evaluated in terms of water yields from forested areas.

Management of phreatophytes and riparian vegetation

Research on phreatophytes and riparian vegetation falls in three categories: hydrologic and ecologic studies, eradication and control measures, and methods for putting water saved to beneficial use. Economic feasibility of control depends on the development of methods for accurately measuring the amount of water used by these plants and their effects on evaporation and seepage losses from streams and canals.

Improved methods of chemical and mechanical control are important, along with studies of the ecology and physiology of these plants. Research on methods of establishing replacement vegetation will lead to more adequate channel stabilization and erosion control. The development of techniques and practices to reduce the flow of water from streams and canals into areas occupied by phreatophytes will also aid in reducing phreatophyte populations.

Management for erosion control

Management of vegetation for water yield must also include management of soil and control of erosion. Sediment reduction is extremely important in the usability of water yields from western lands and in the management of cultivated and other lands where sediment-laden water is used.

Research in erosion control includes research in management methods to prevent soil losses from occurring and in methods of rehabilitating lands already eroding, and maintaining them in stable condition. Development of these methods requires fundamental studies of soils, climate, plant breeding, and ecology. Selection, development, and testing of new plant species and varieties are needed. Mechanical treatments, which have improvement of vegetative cover for maximum erosion control as their primary purpose, should be evaluated in terms of quality and quantity of water yields.

Water yields from small and large watersheds

Limited research data and many streamflow studies indicate that streams, channels, and river valleys take heavy tolls of water yield from upland areas. Runoff from upstream research plots and small watersheds in the West are often two to four times as large per unit area as measured in the flow of rivers. Downstream abstractions from onsite runoff are not understood. Watershed research to date has not bridged the gap in water yields between small and large areas.

Economic research

As research in water yields is planned it is desirable that economic research also be included. Consideration of vegetation management and water yield relate to some basic economic questions: (*a*) What is an optimal water yield derived by altering the amount and kind of vegetation on a watershed? (*b*) Should water yield be maximized consistent with minimum requirements for the protection of watersheds to provide maximum water supplies for offsite uses? (*c*) Should all watershed and offsite uses be reconciled in terms of broad social objectives in a multipurpose planning framework, with watershed management methods and resultant water yields forming only one aspect of an overall optimal water allocation?

Whatever the overall objectives of management might be, methods of analysis that adequately evaluate both the monetary and intangible benefits associated with using forest, grazing, and agricultural areas for different onsite and offsite purposes have not yet been developed. Also, careful study should be given to the economics of certain treatment practices such as benefits and costs of sacrificing timber growth for increased water yield and the benefits of increased water yield accruing to various offsite users. Related to this are possibilities for entirely converting vegetation from brush to pasture or trees. Furthermore, vegetation management as a means for reducing floodflows and improving water yield quality through sediment reduction needs to be economically related to structures intended to stabilize streamflow but susceptible to siltation from upstream erosion.

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